Lectures on radio astronomy: 6

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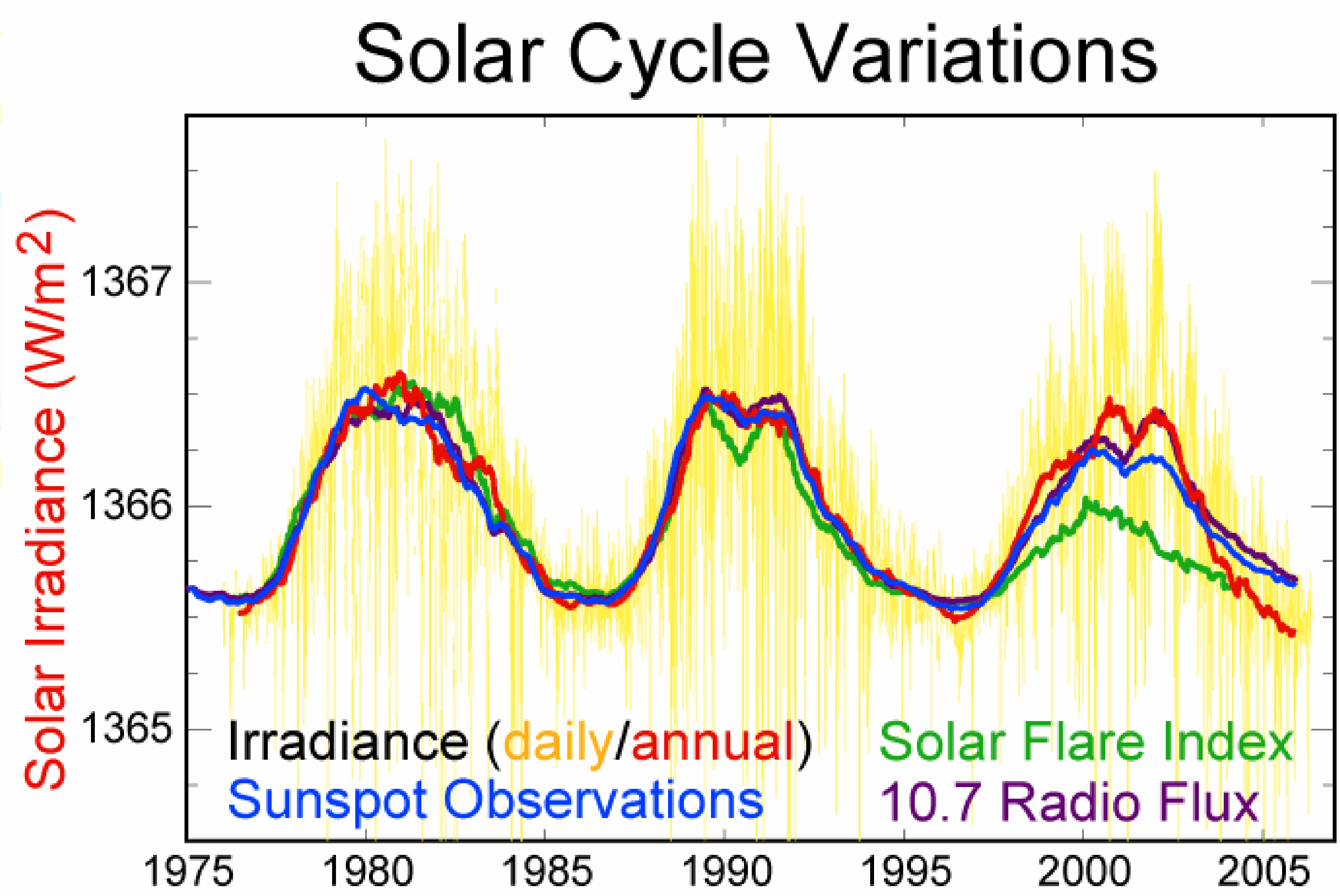
Galactic & extragalactic radio astronomy

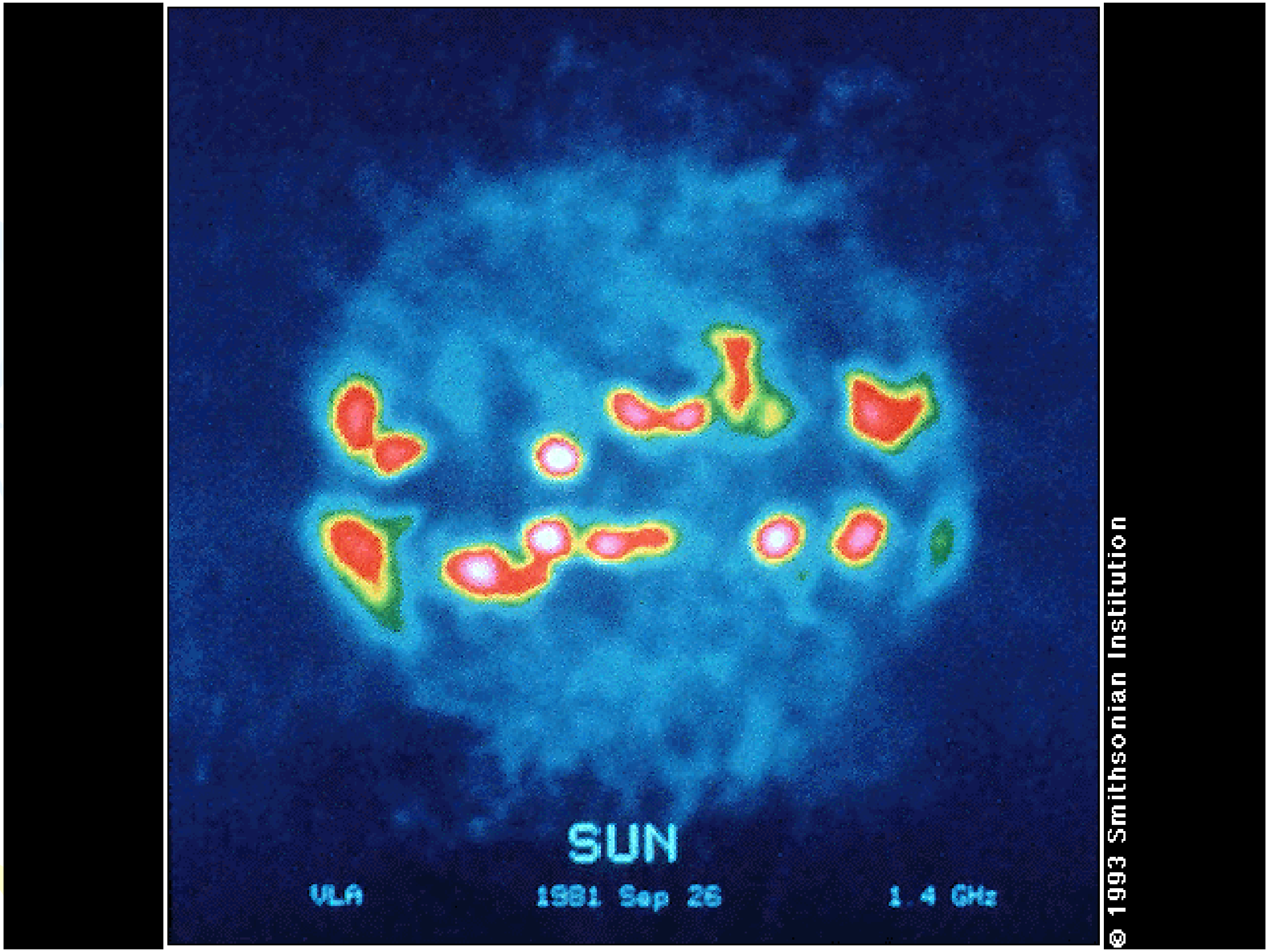
Solar system

- Radio emission can be observed from many bodies in the solar system
- Both the active and quiet sun emit radio waves
- Planets can be observed as thermal sources (black body radiation)
- Magnetic planets have radio emitting radiation belts
- Comets emit 18 cm OH line radiation

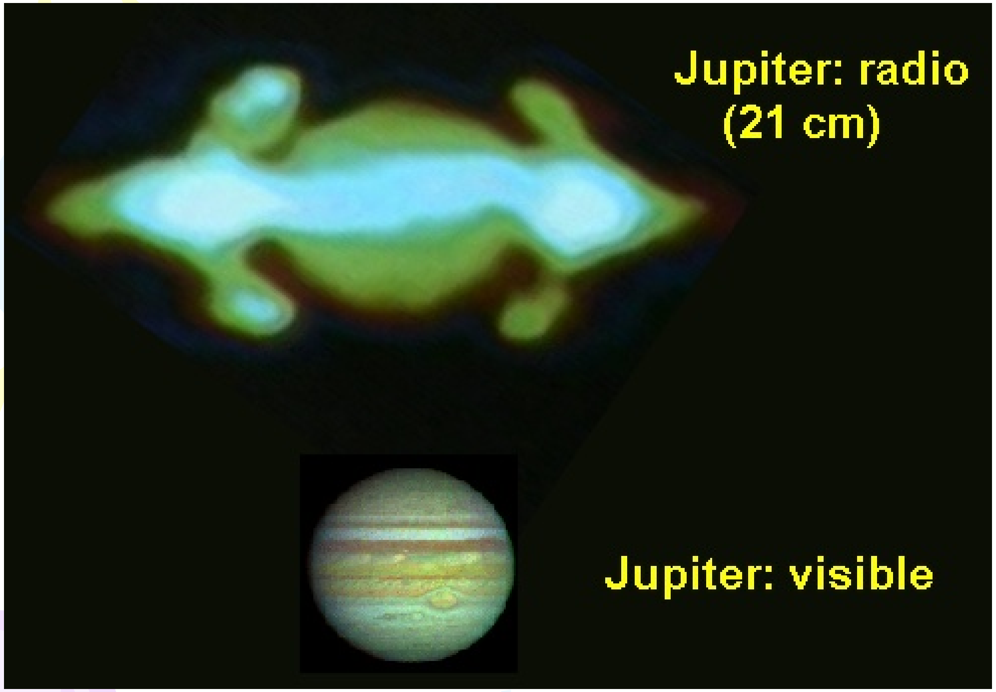
Radio emission from sun correlates well with solar activity

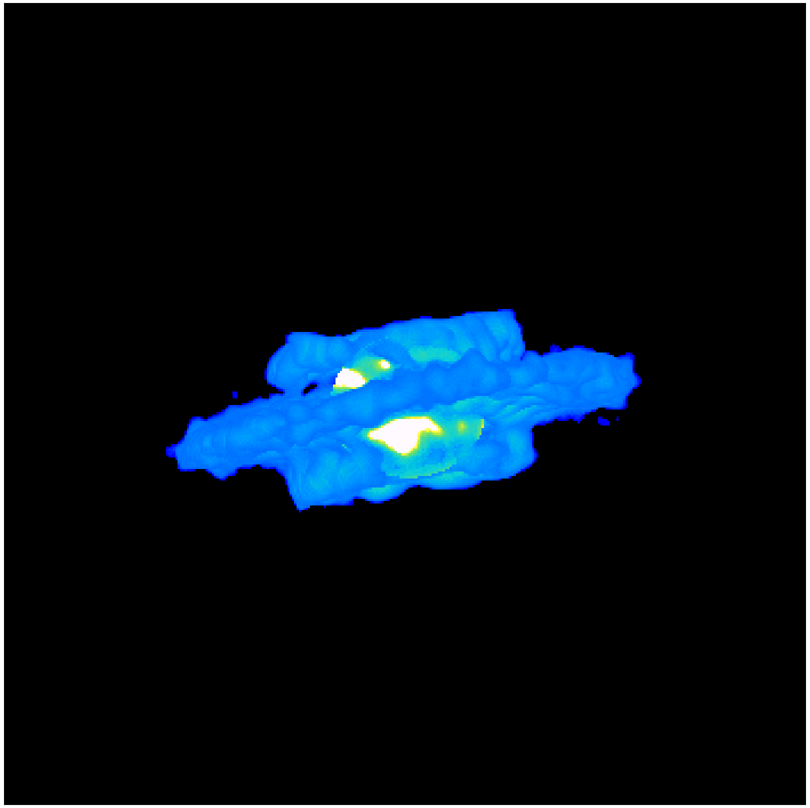


Radio image of sun showing disk and active regions



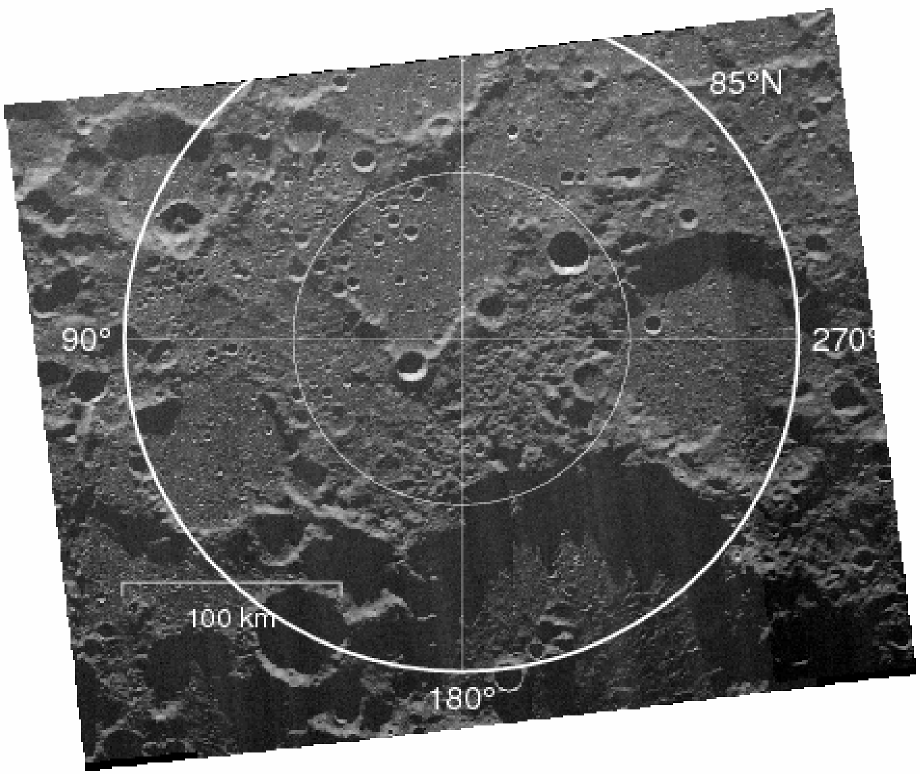
Radio emission from Jupiter's radiation belts

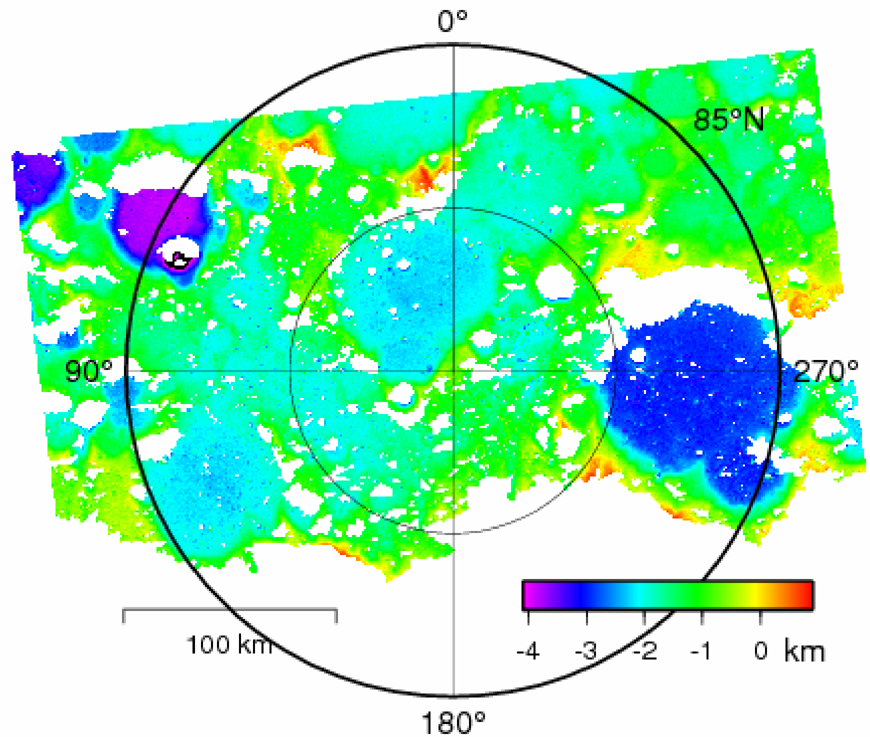




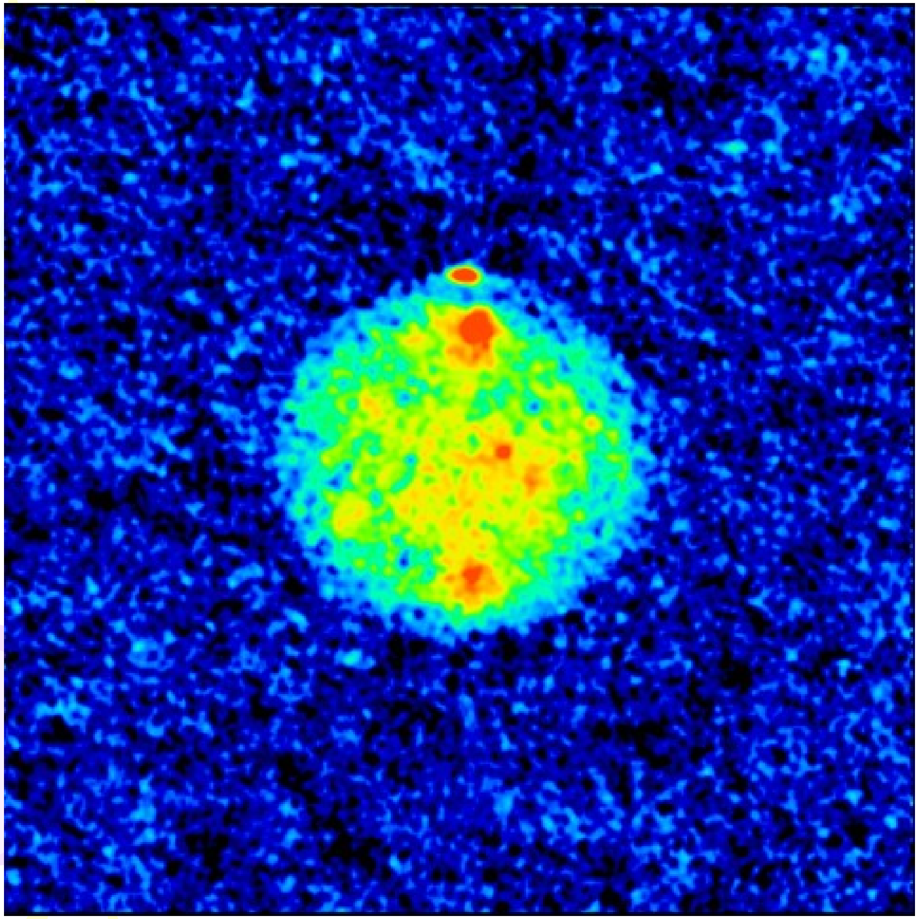
We also use radar to study objects in the solar system

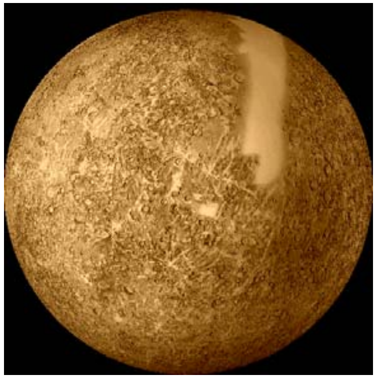
Modern lunar image near the north pole, and elevation in color



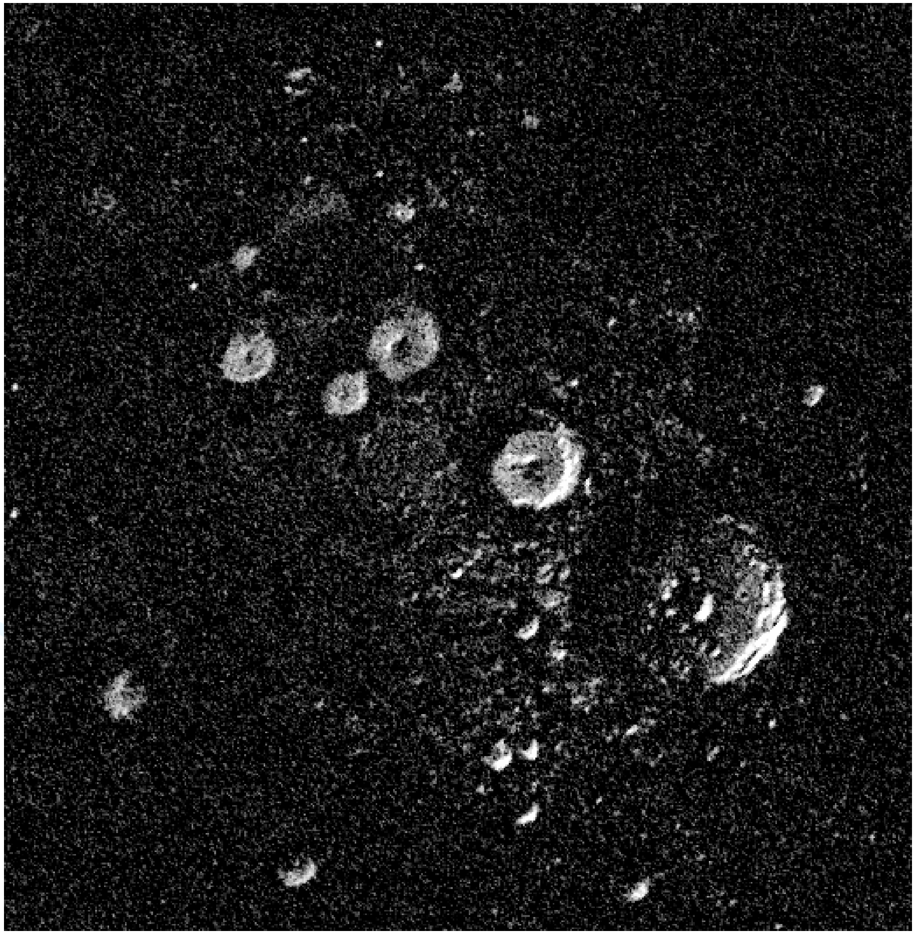


Radar image of Mercury – ice near north pole?

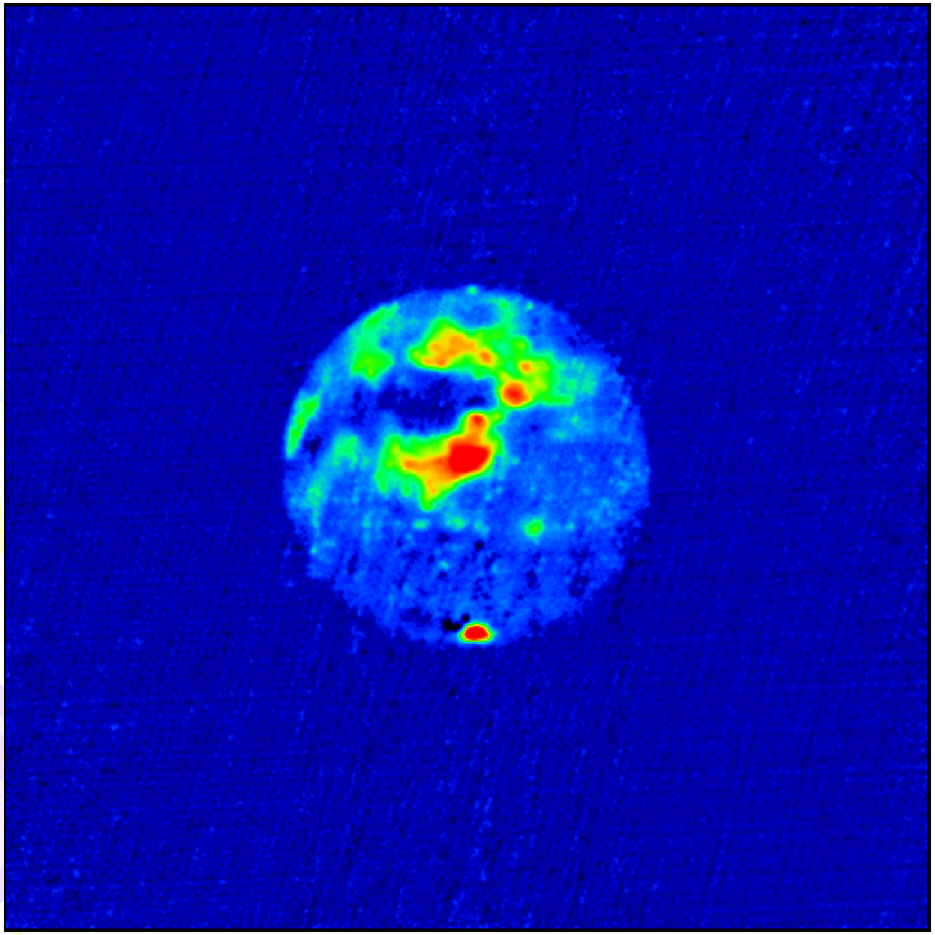


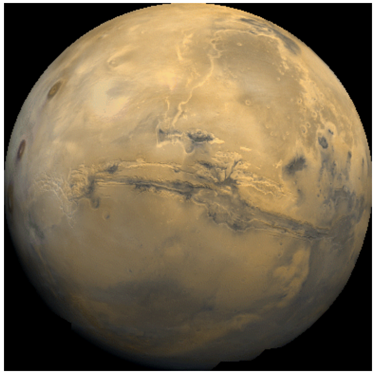


Arecibo delay-Doppler radar image of Mercury's north pole, showing ice deposits (size ~ 300×300 km^2)

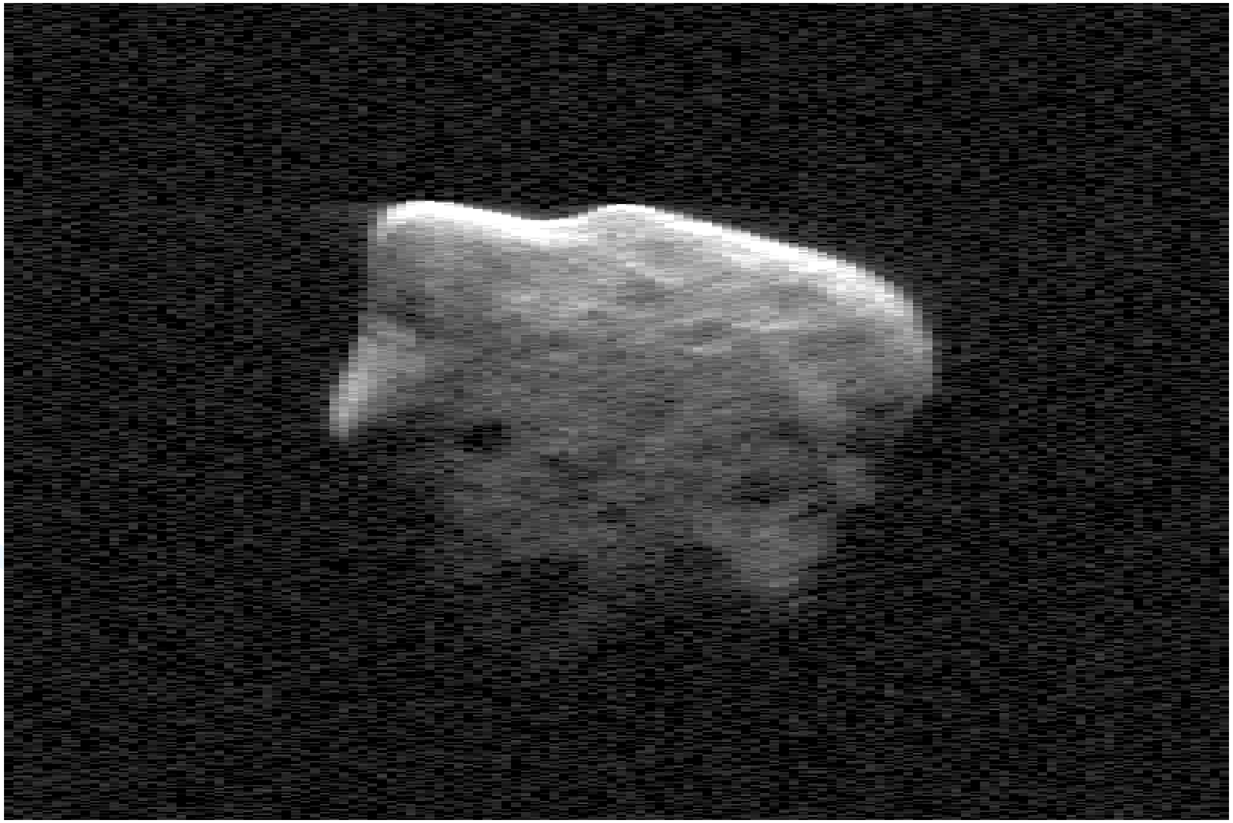


Radar image of Mars – again likely polar ice





Arecibo delay-Doppler radar image of NEA 1999 JM8 (*D* ~ 3 km)

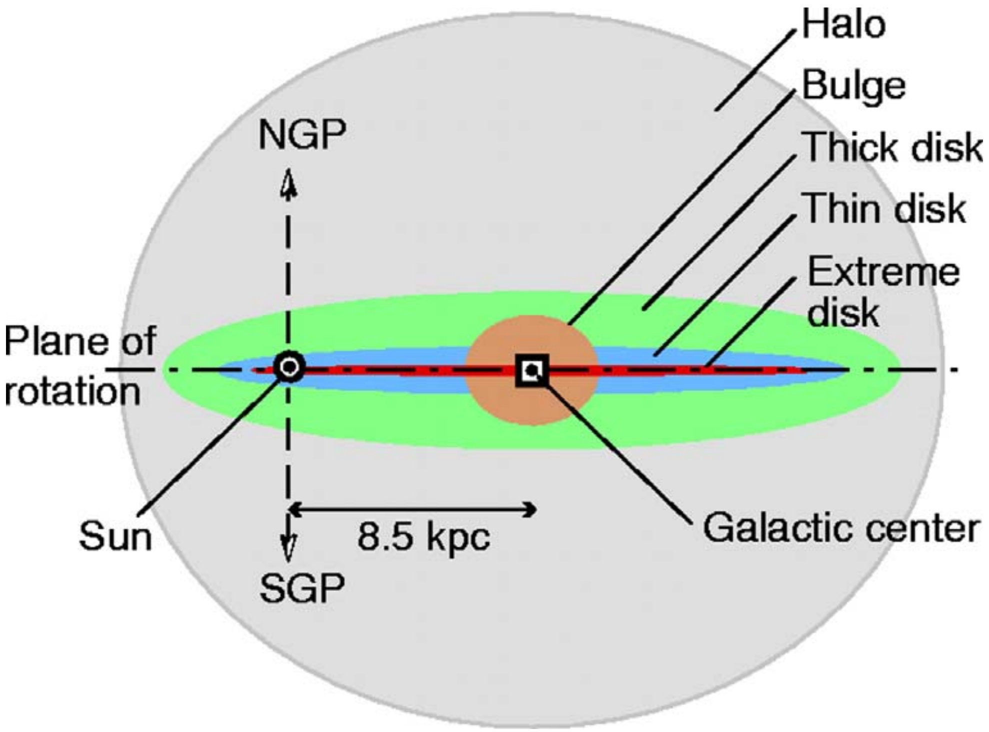


Radio emission from the Milky Way

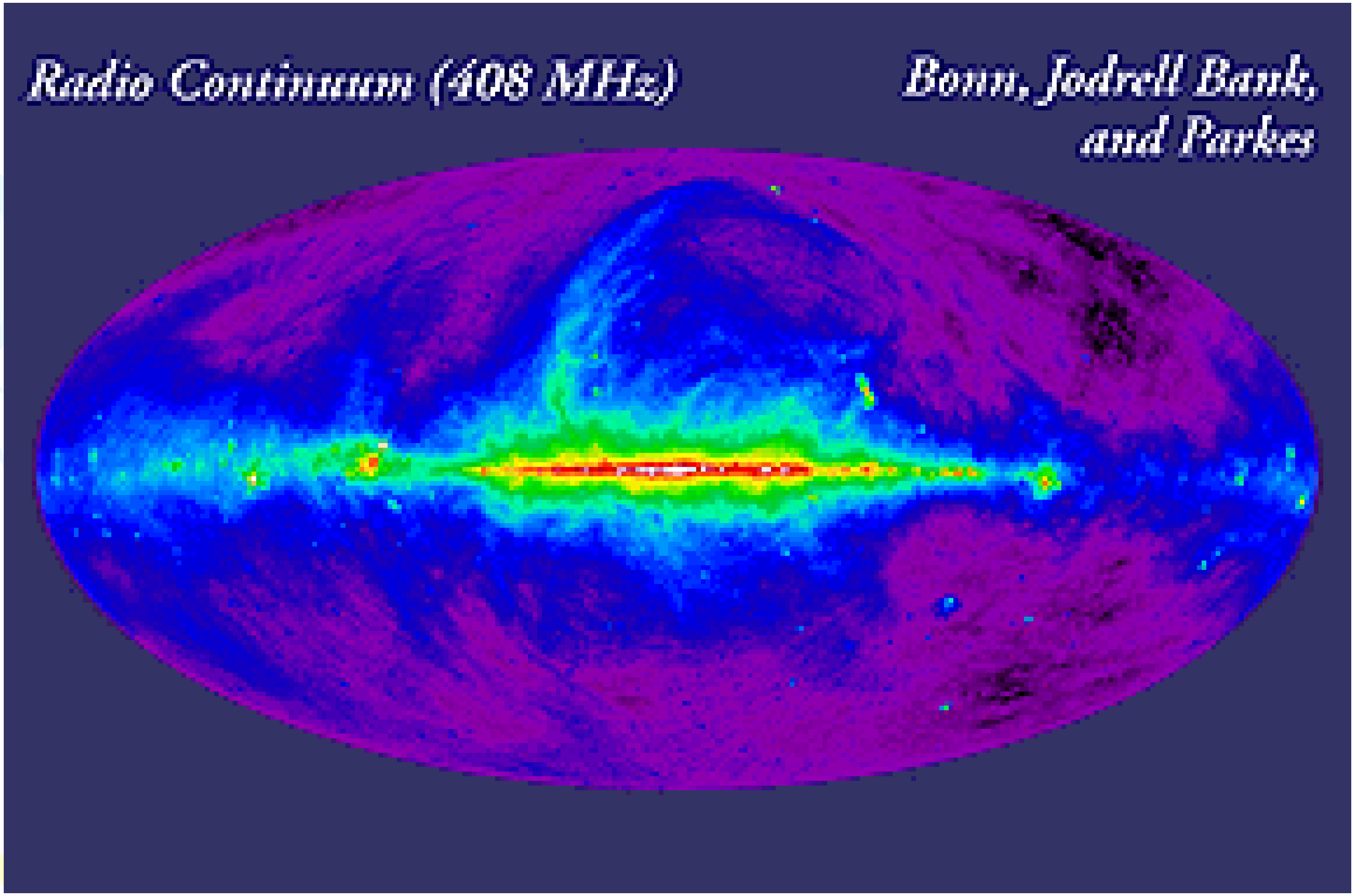
- We observe: diffuse continuum emission from the disk
- 21 cm HI line emission from clouds
- Weak radio emission from all star types
- Radio emission from glowing HII clouds ionized by light from hot, young stars
- Some 275 radio supernova remnants
- Neutron stars observed as pulsars

Let's look at some of the types of Milky Way (MW) emission

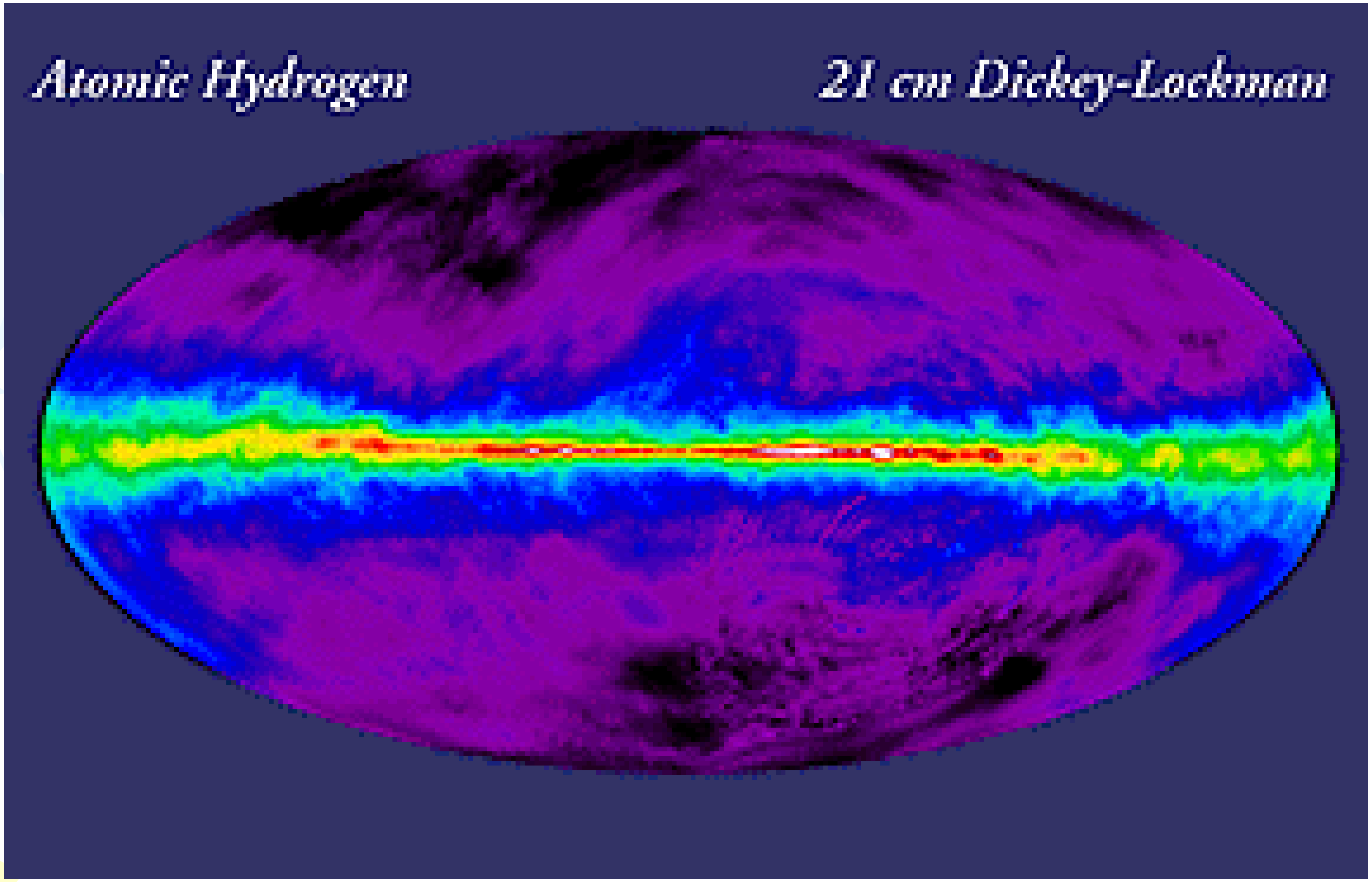
- Sketch shows main structures of MW
- Most objects to be discussed are in thin disk
- Associated with star formation...
- ...and star demise
- First, diffuse gas



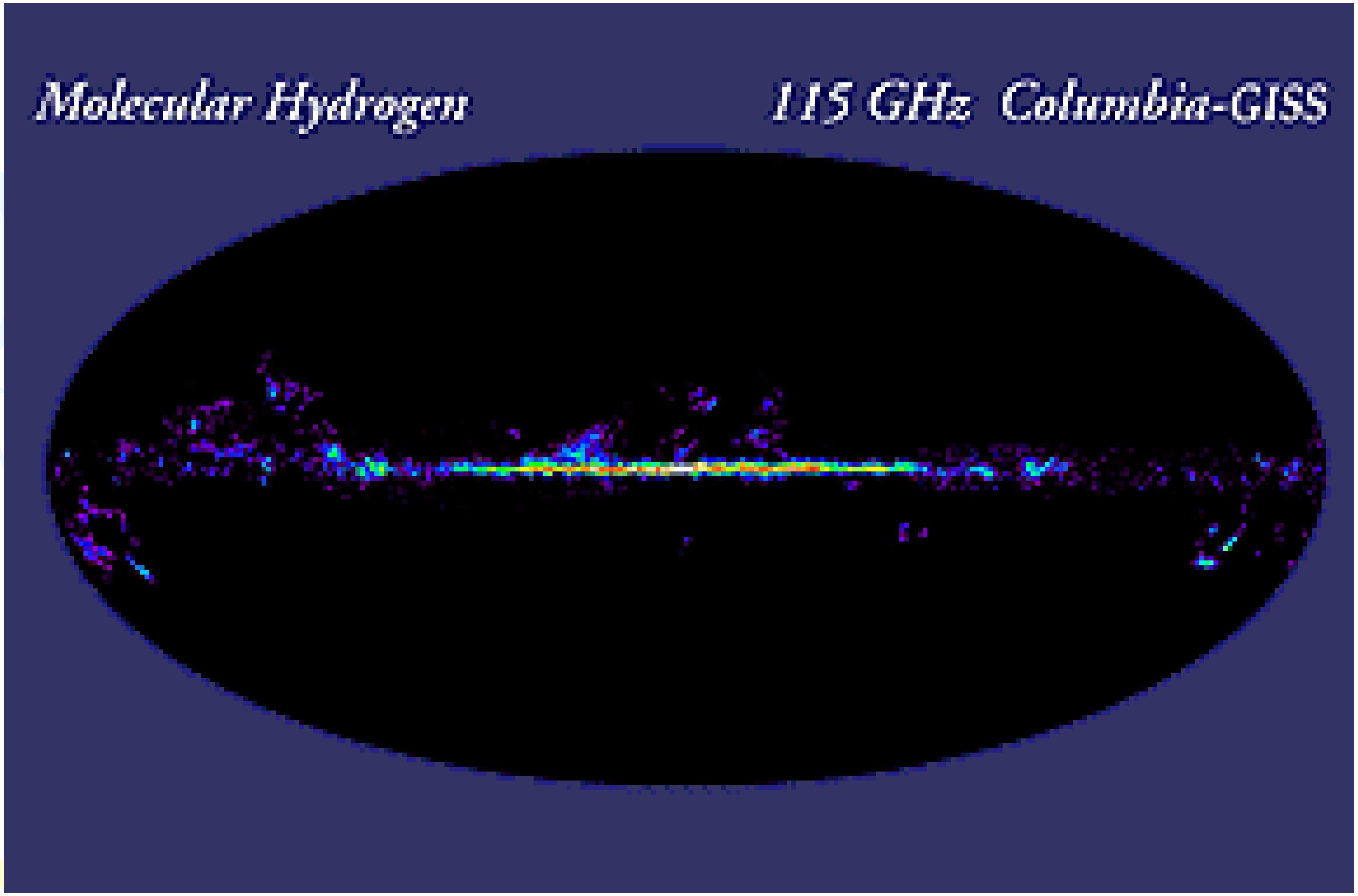
In radio continuum, we see through the whole Milky Way



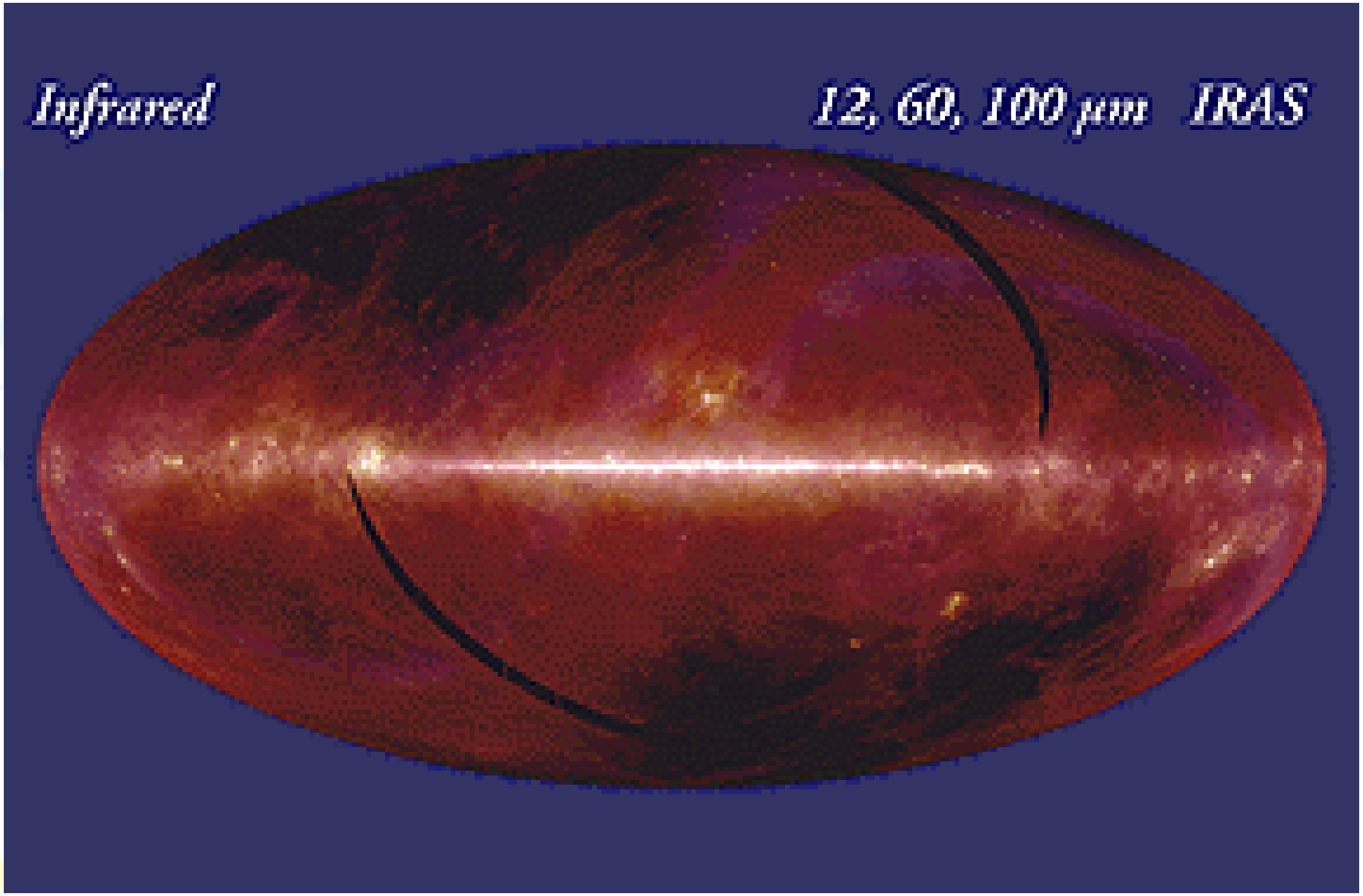
Dust also has no influence on the 21 cm HI line



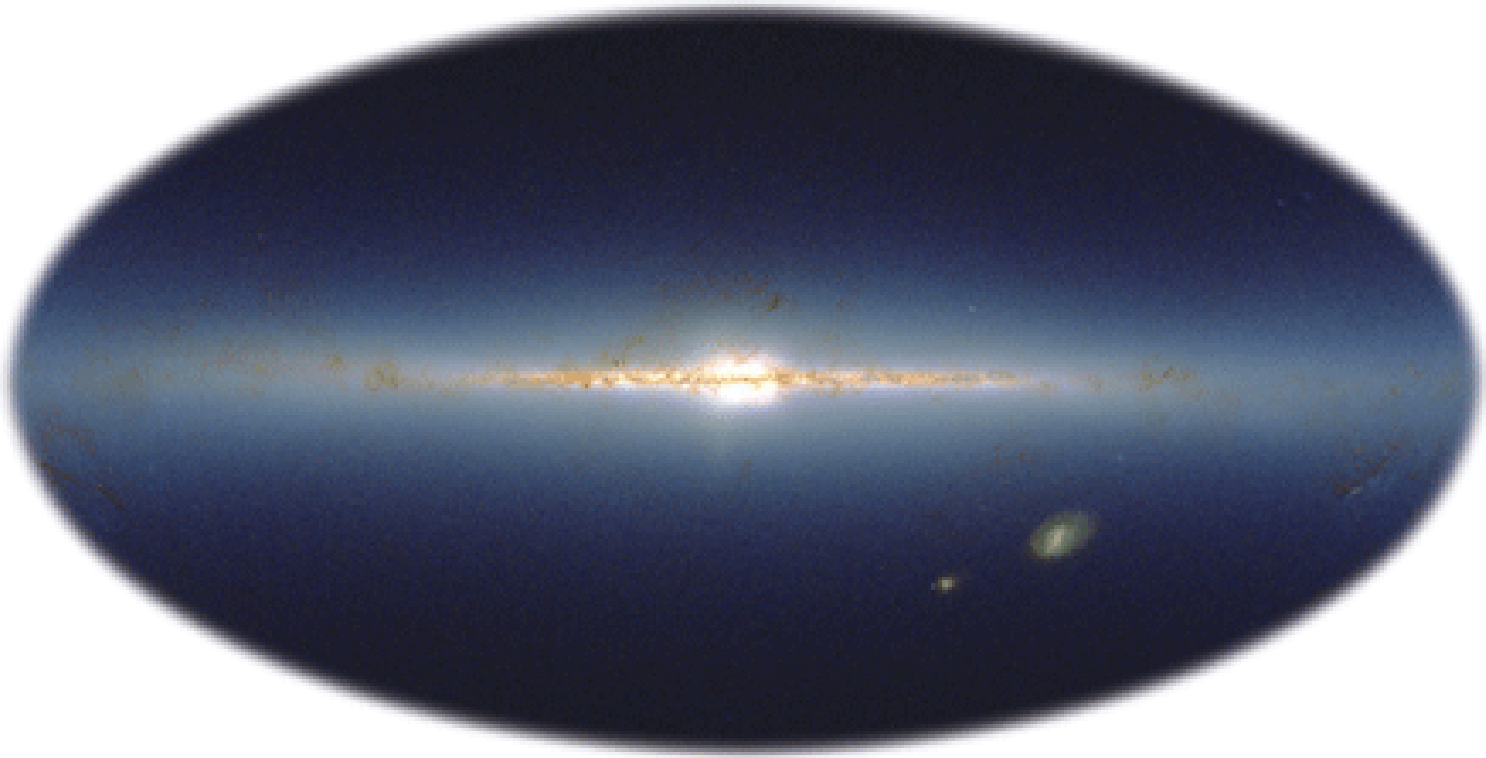
The CO line at 2.6 mm is a surrogate for H_2



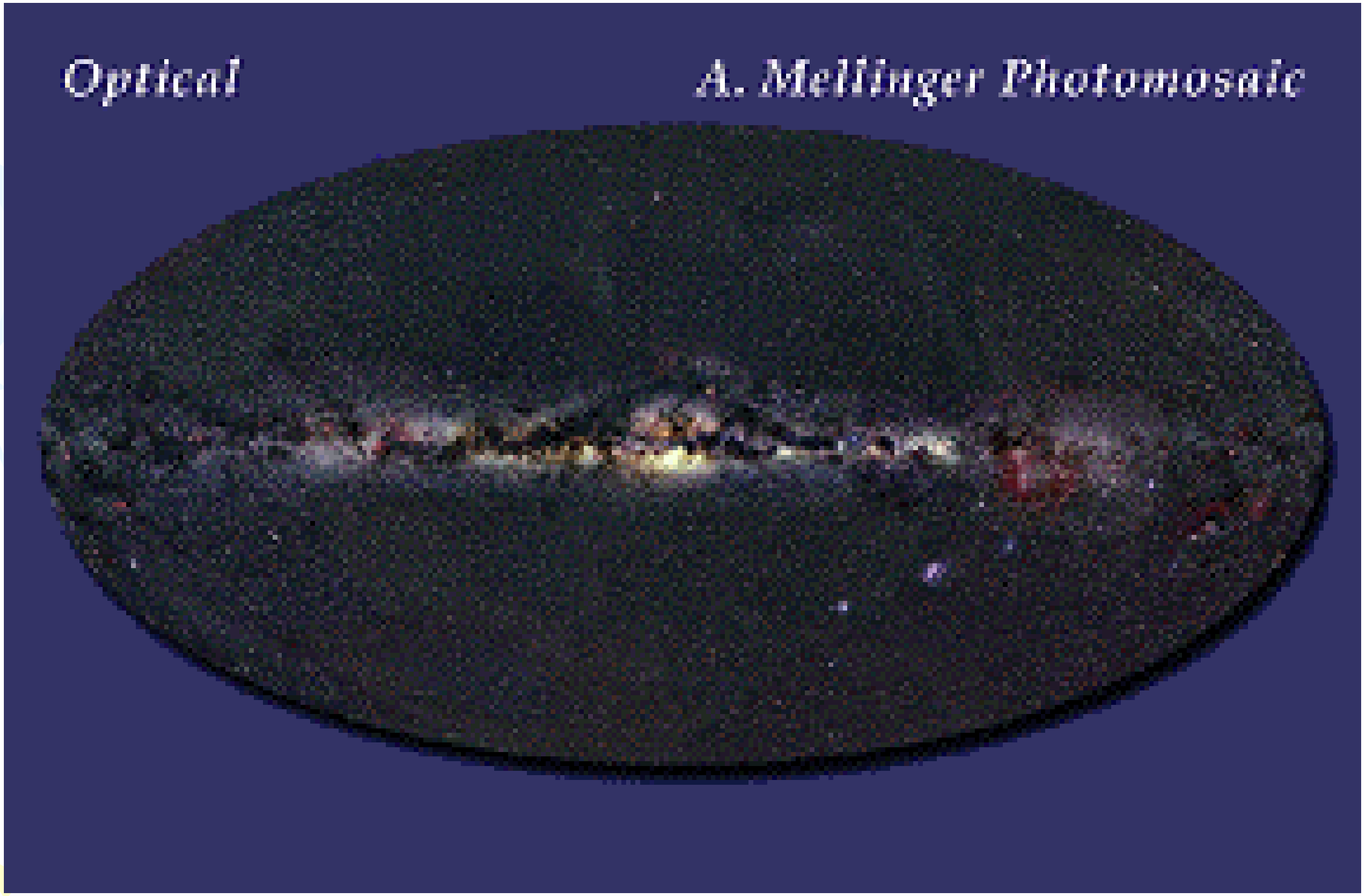
Most IR emission is unblocked (and comes from hot dust)



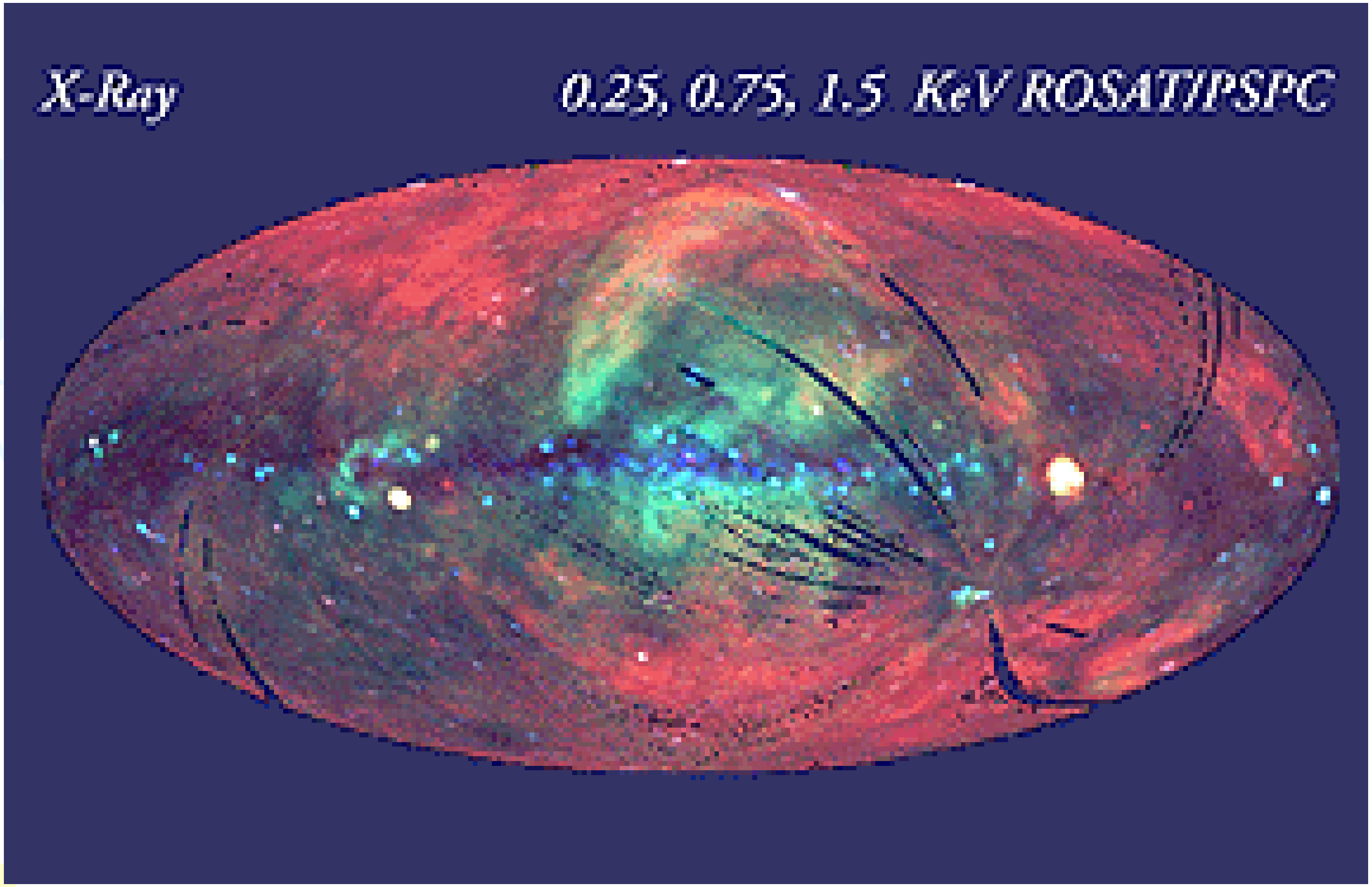
Near IR (2 μm) shows bulge unobstructed by dust



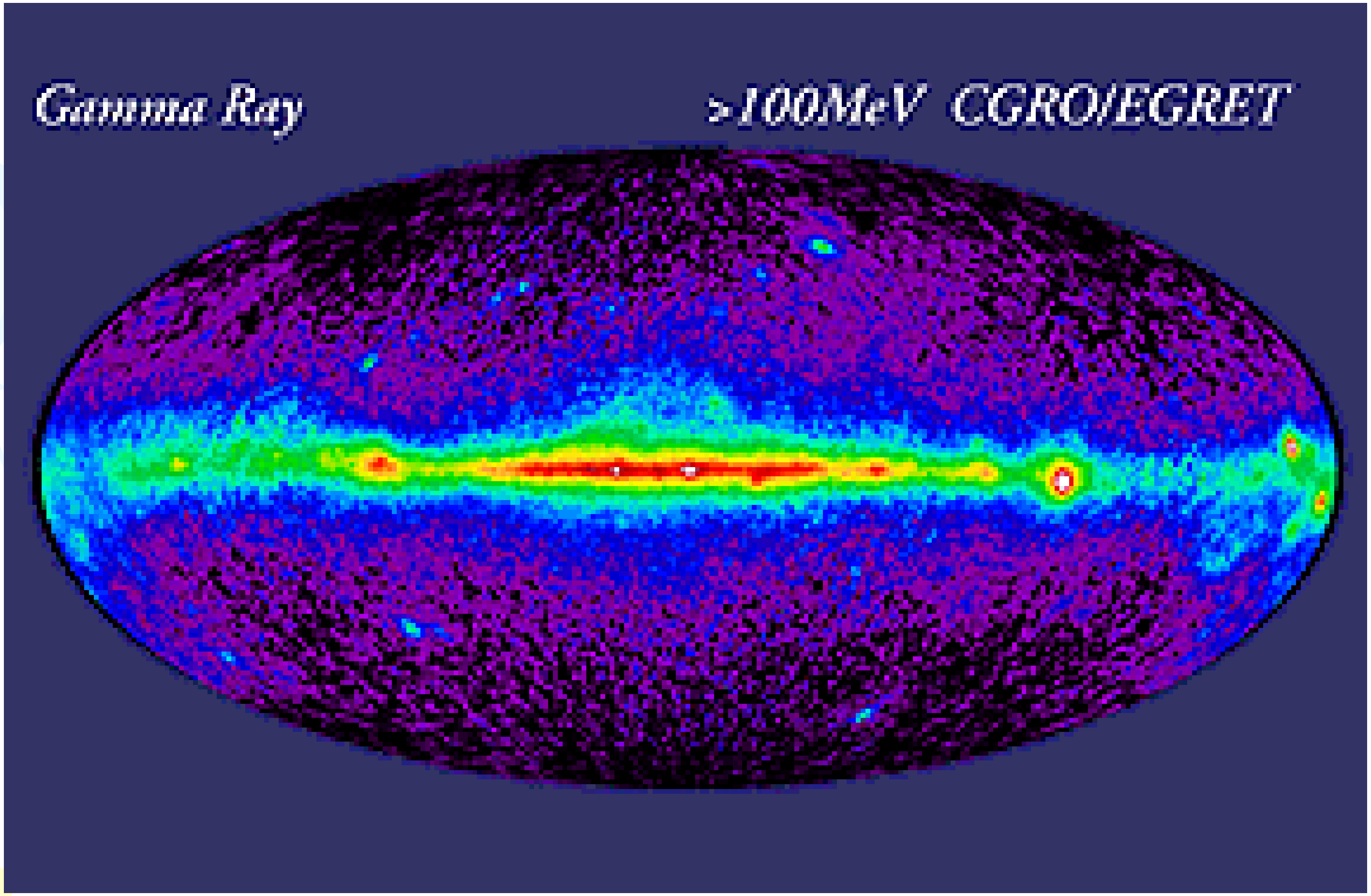
In the galactic plane, little light gets through the dust



Low energy X-rays, absorbed by gas in plane of Galaxy



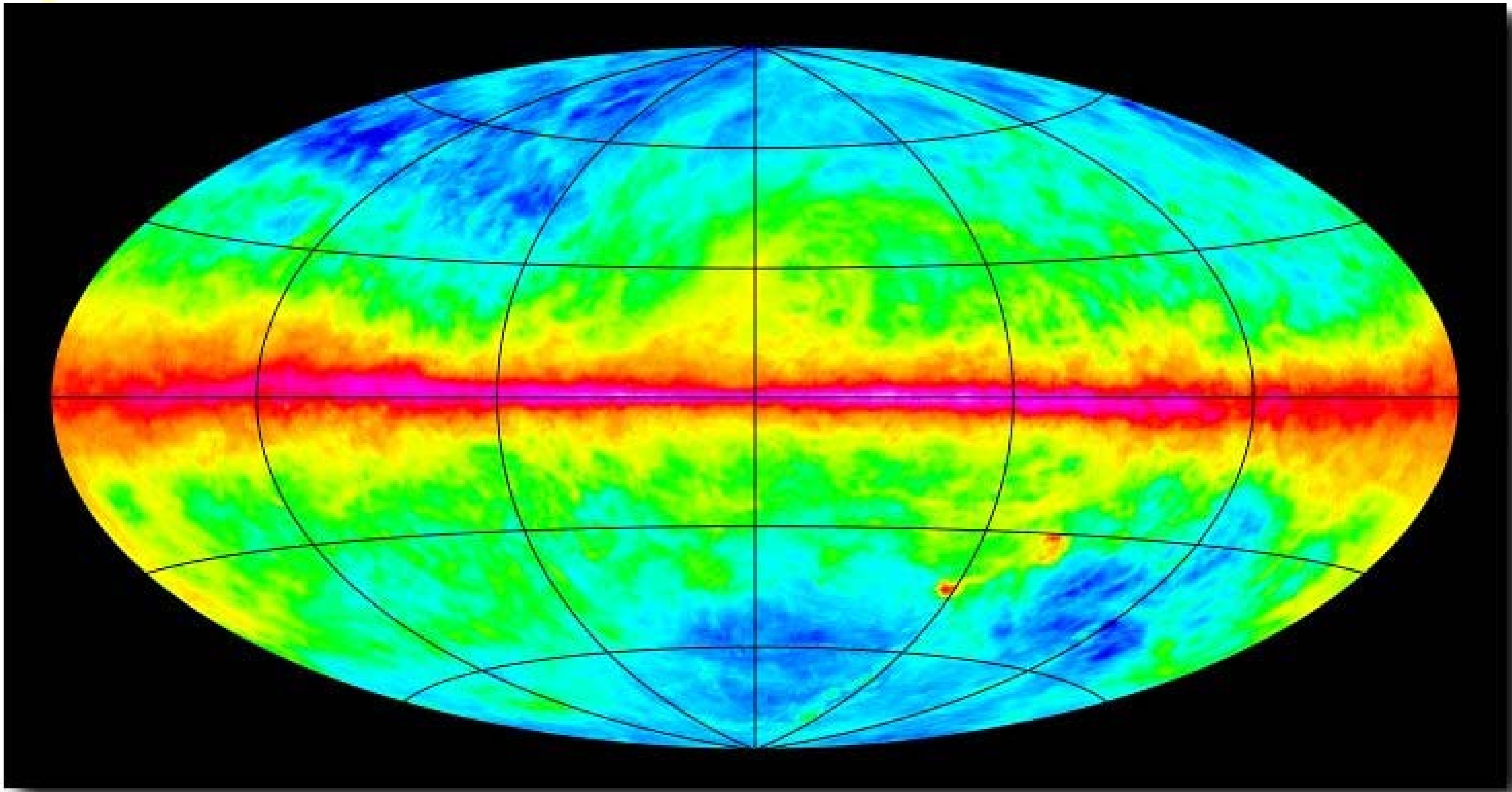
High energy γ-rays, unobstructed and closely linked to gas



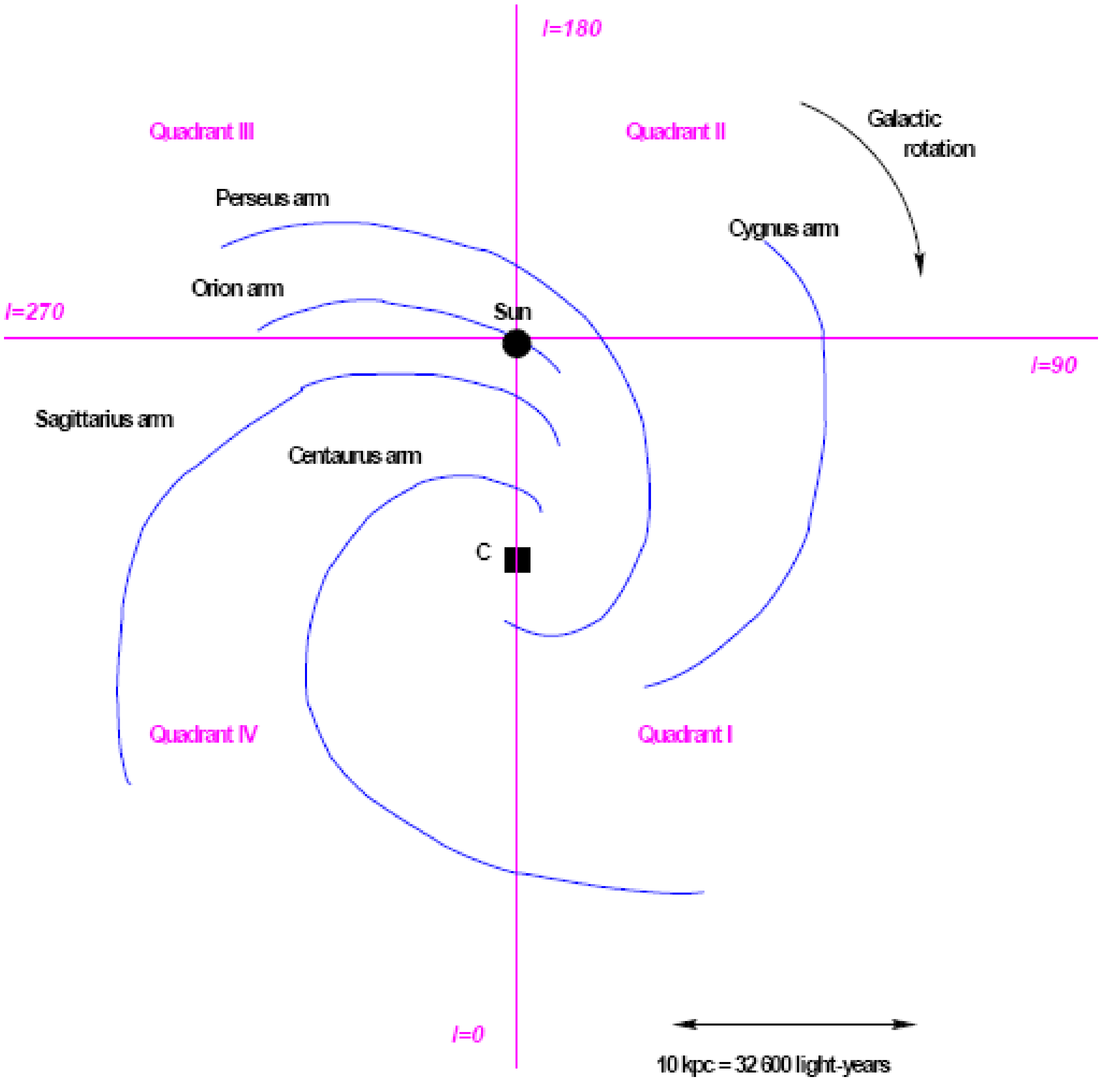
These images show both diffuse and discrete sources

- The 21 cm HI and 2.6 mm CO mainly come from diffuse clouds of H and H_2
- Much of the 408 MHz radio continuum is from discrete sources (clouds of ionized gas, shocks from supernovae)
- X-ray emission from hot, shocked gas, and from binaries & various stars
- IR from hot dust and cool stars

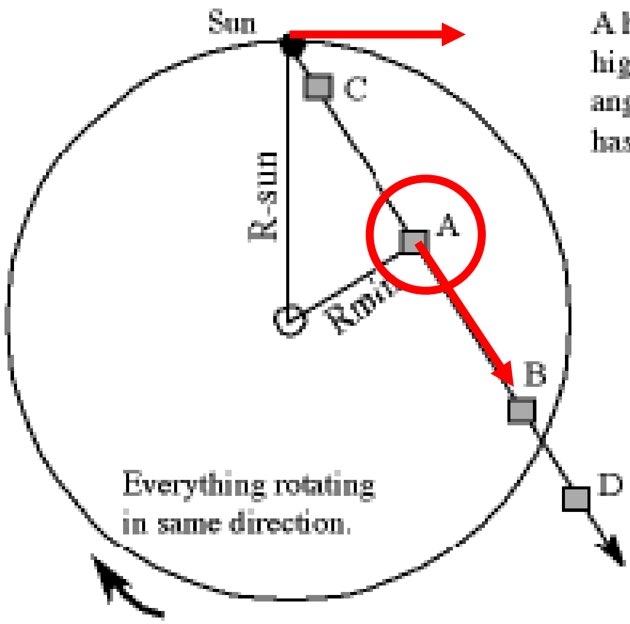
Milky Way is difficult to study because we are in it



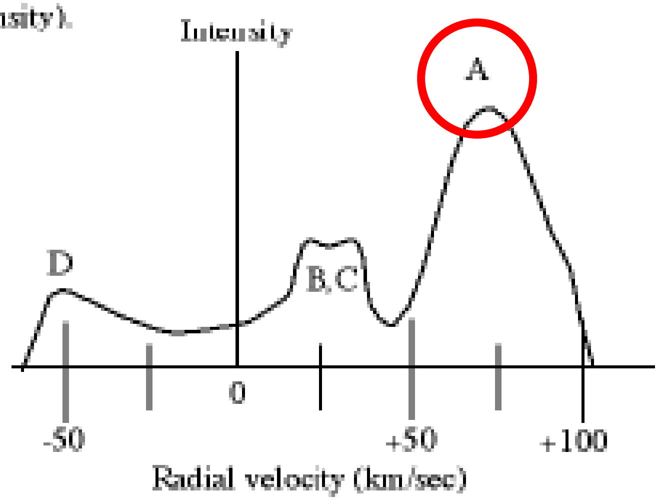
4 quadrants: I & III, gas moves away; II & IV, gas approaches



To map motion in Milky Way we must assign peaks to locations

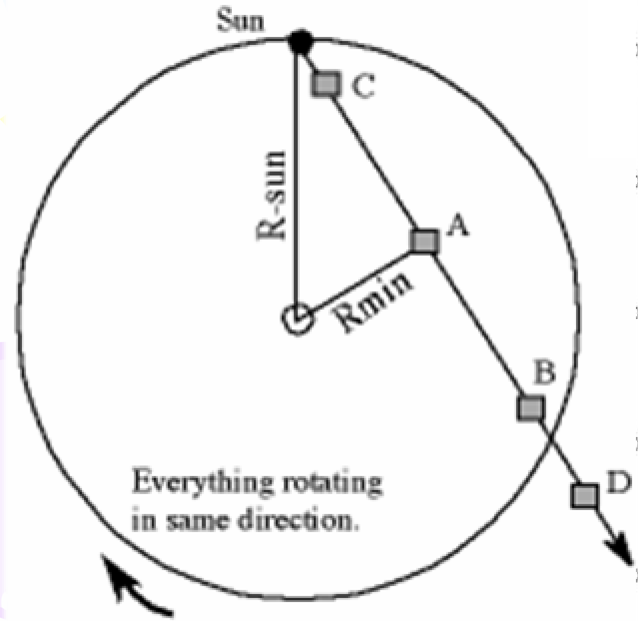


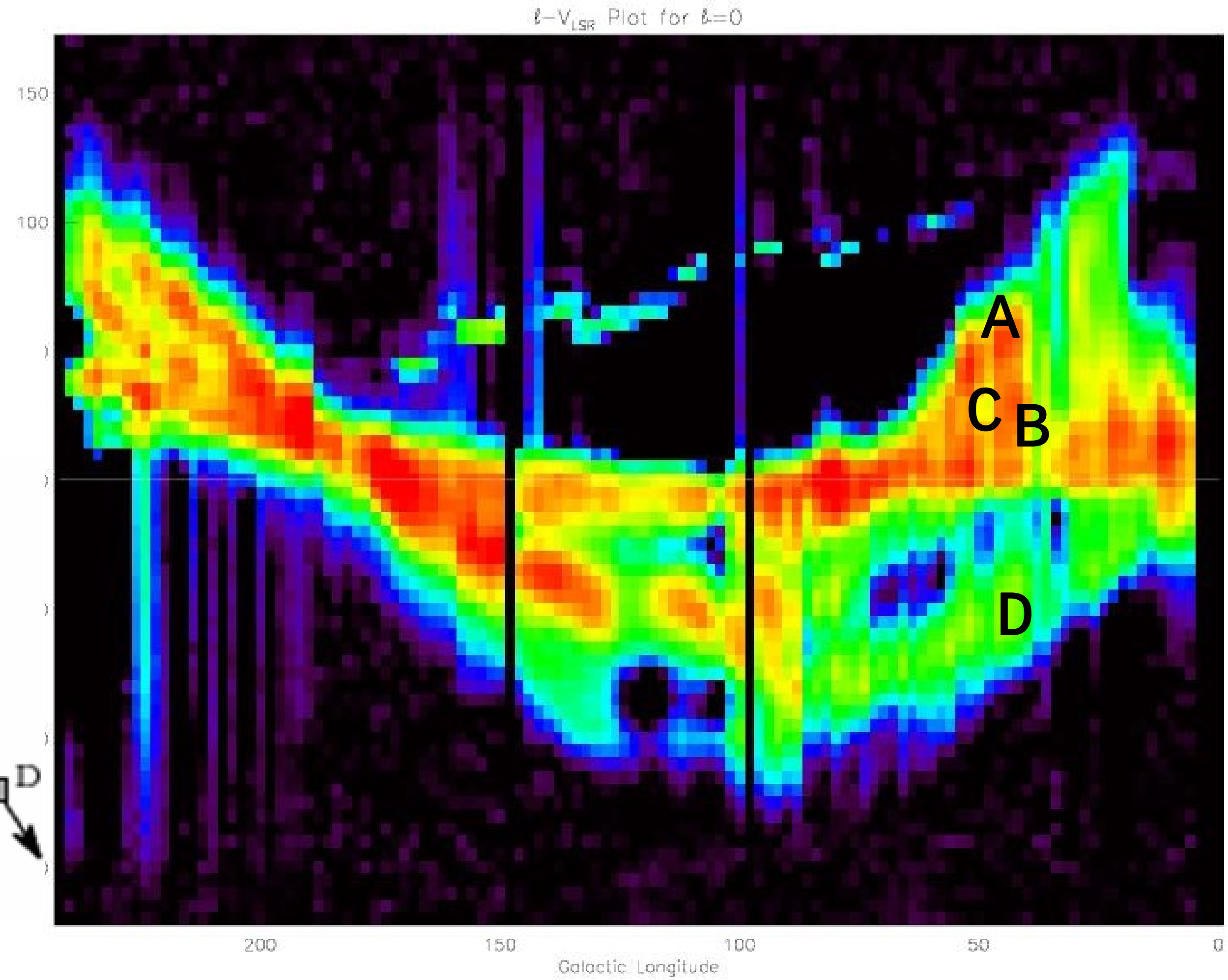
A has greatest angular speed and moving fastest away from sun. A has higher density of H. B & C moving at about same angular speed > sun's angular speed. D is outside solar distance–slower angular speed and has less materal (density).



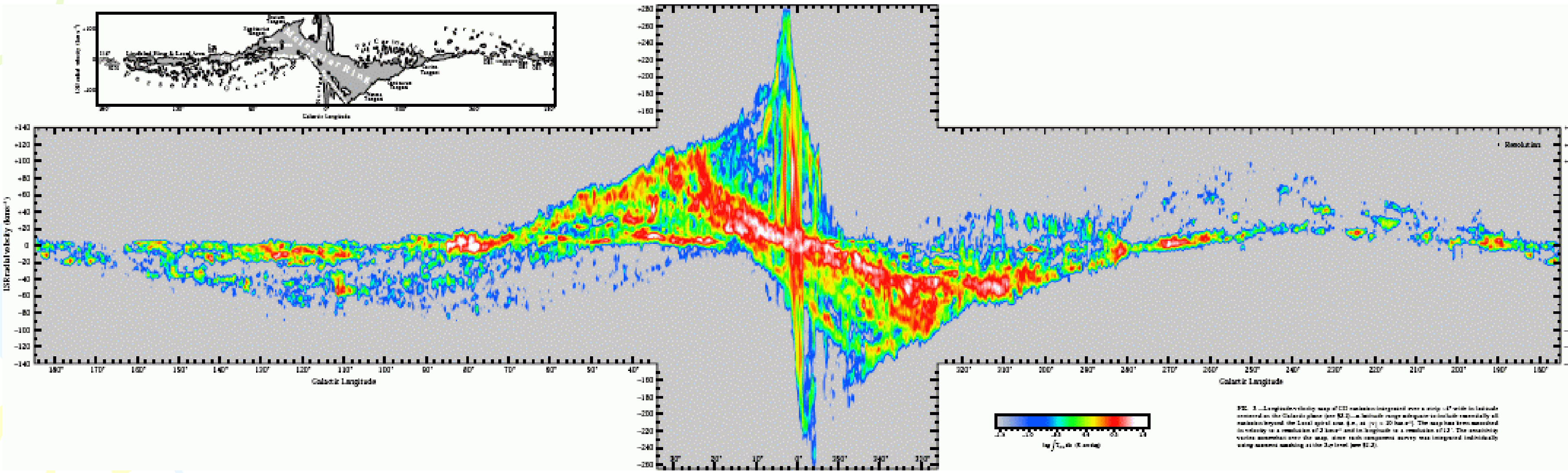
Four clouds all in the same direction. Use doppler shifts to distinguish one cloud from the other. Use the rotation curve to convert the doppler shifts of each cloud to distances from the center of the Galaxy. Do this for other directions to build up a map of the Galaxy strip by strip.

Here's the HI in the Milky Way disk, as position vs. velocity



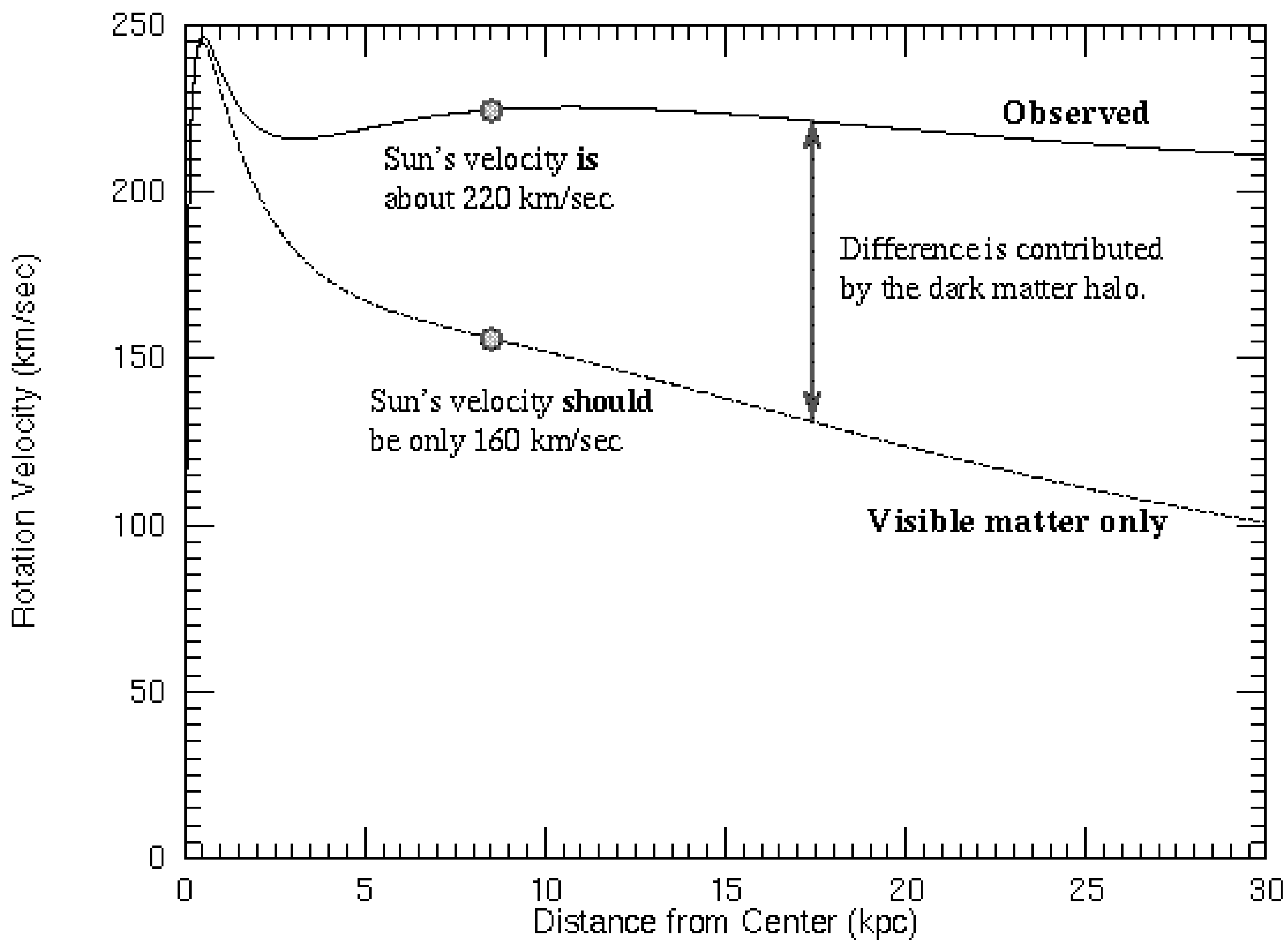


The line emission (especially HI and CO) gives speed of gas



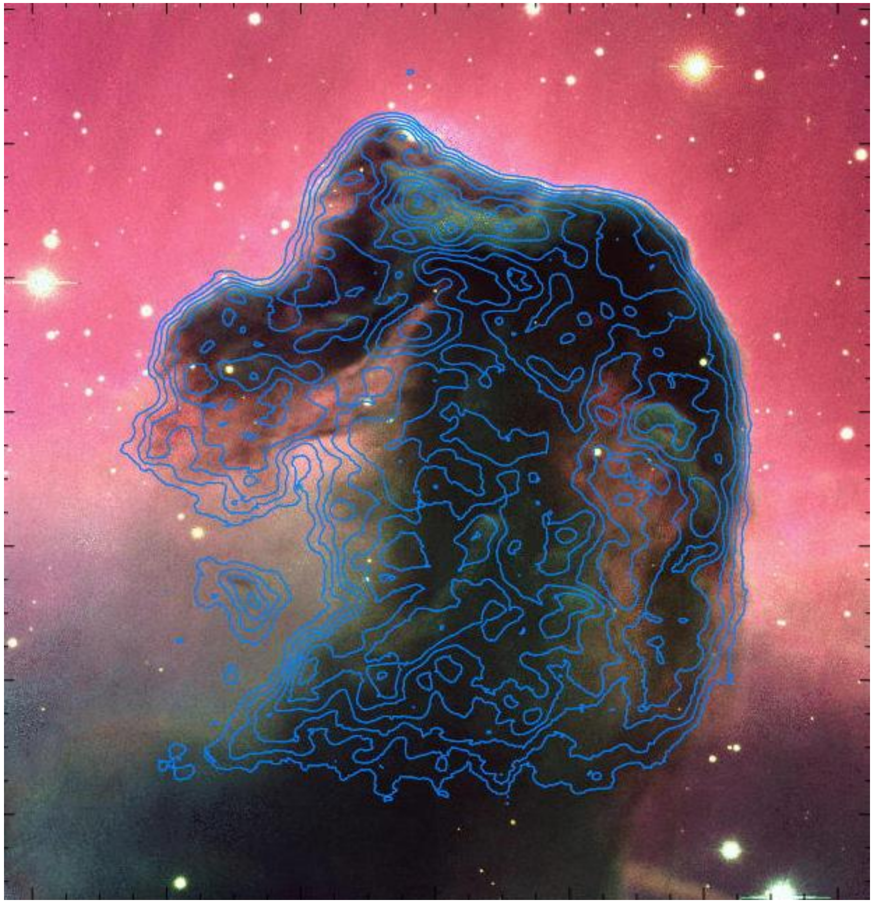
- Here is CO in the plane of the MW, showing the motion of gas relative to the Sun
- Positive velocity moving away from us
- Negative velocity gas moving toward us

Orbital speed in MW is almost constant outside of center



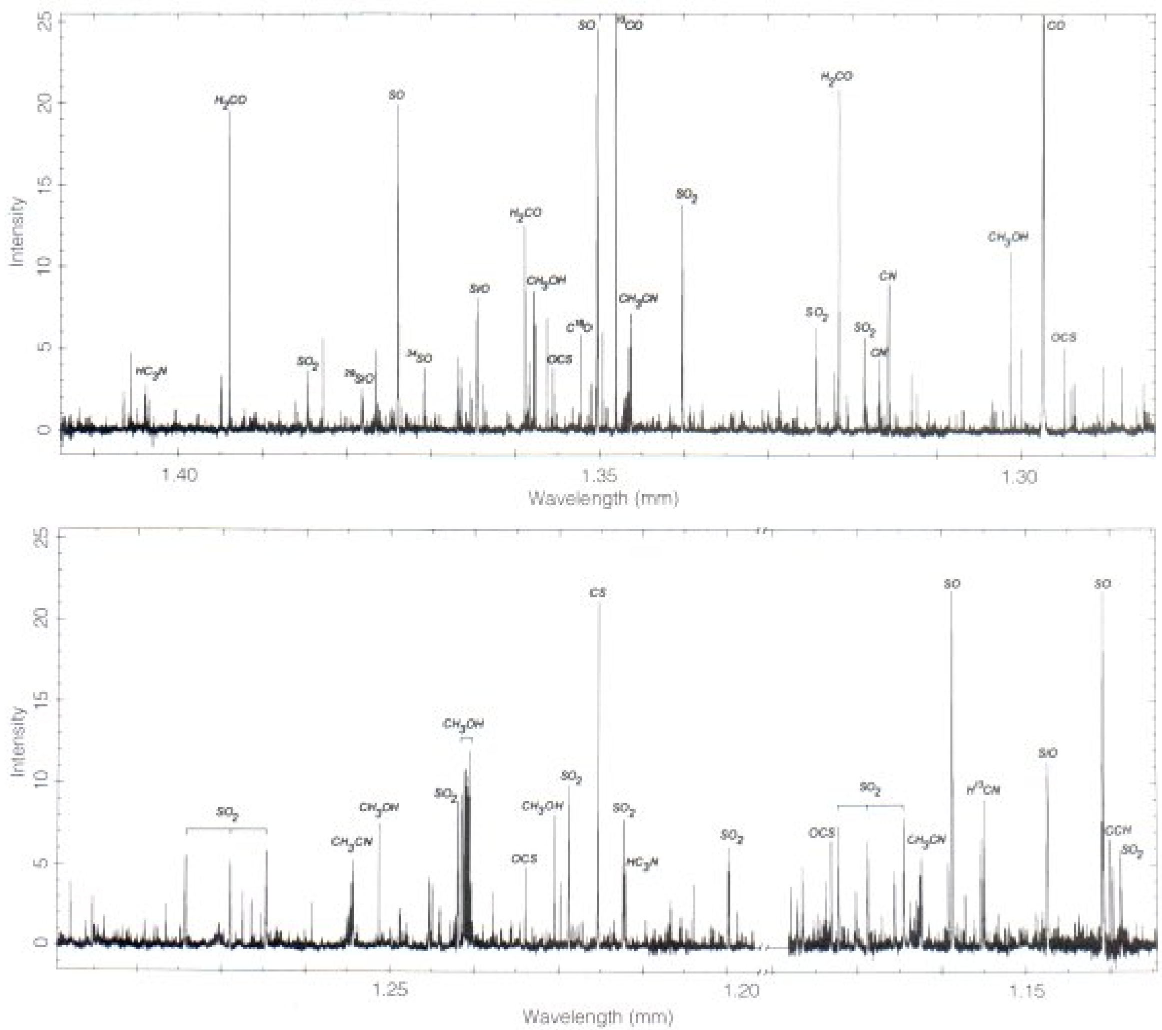
Large complexes of dust, H II regions, molecules: cradle of stars

New stars – proto-stars – are usually shrouded in dust

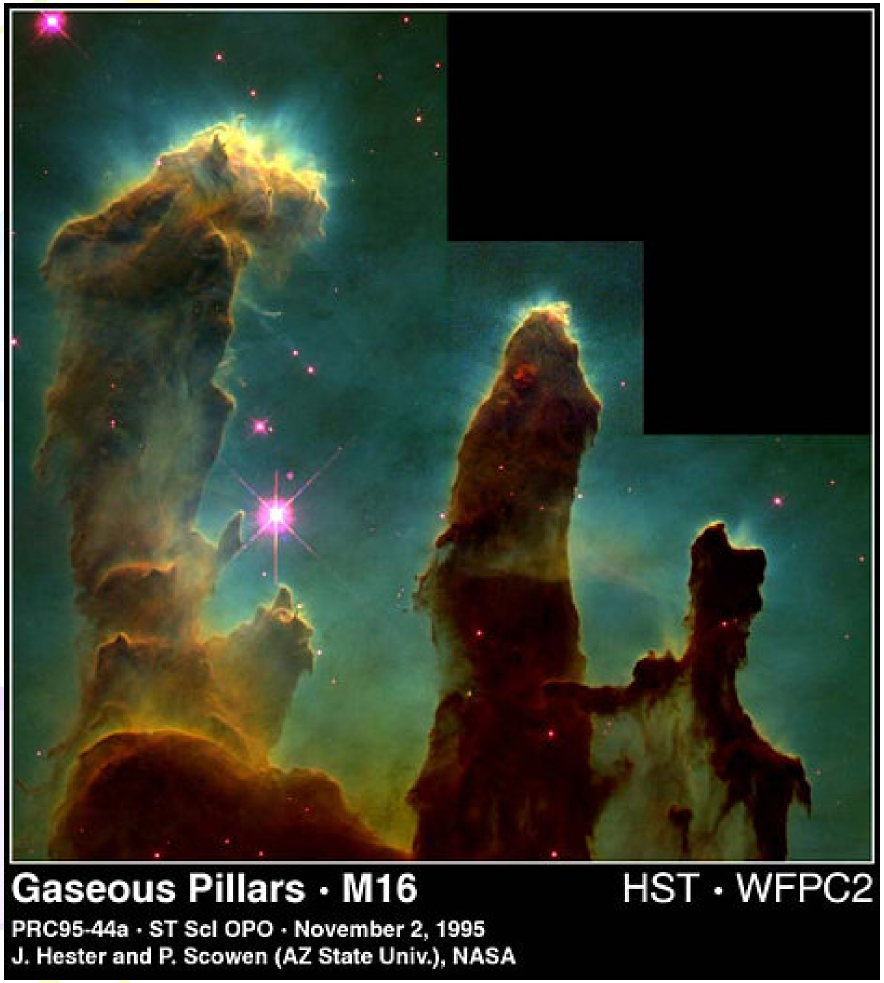


Molecules (CO) also present in dust clouds

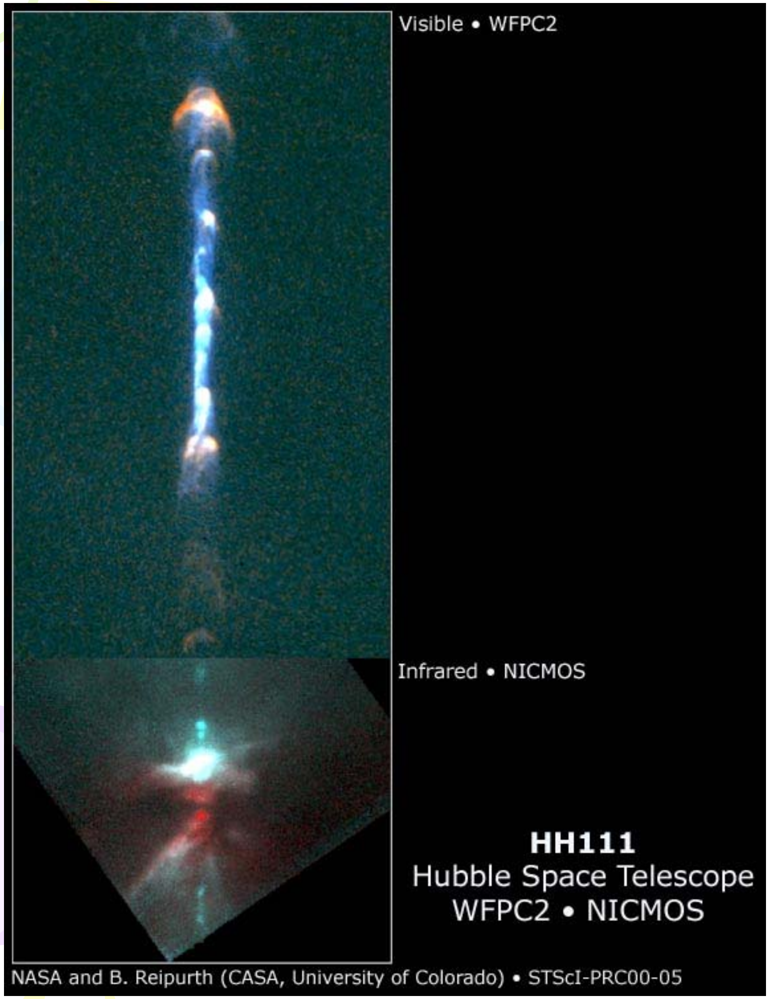
Millimeter band is particularly rich in molecular emission

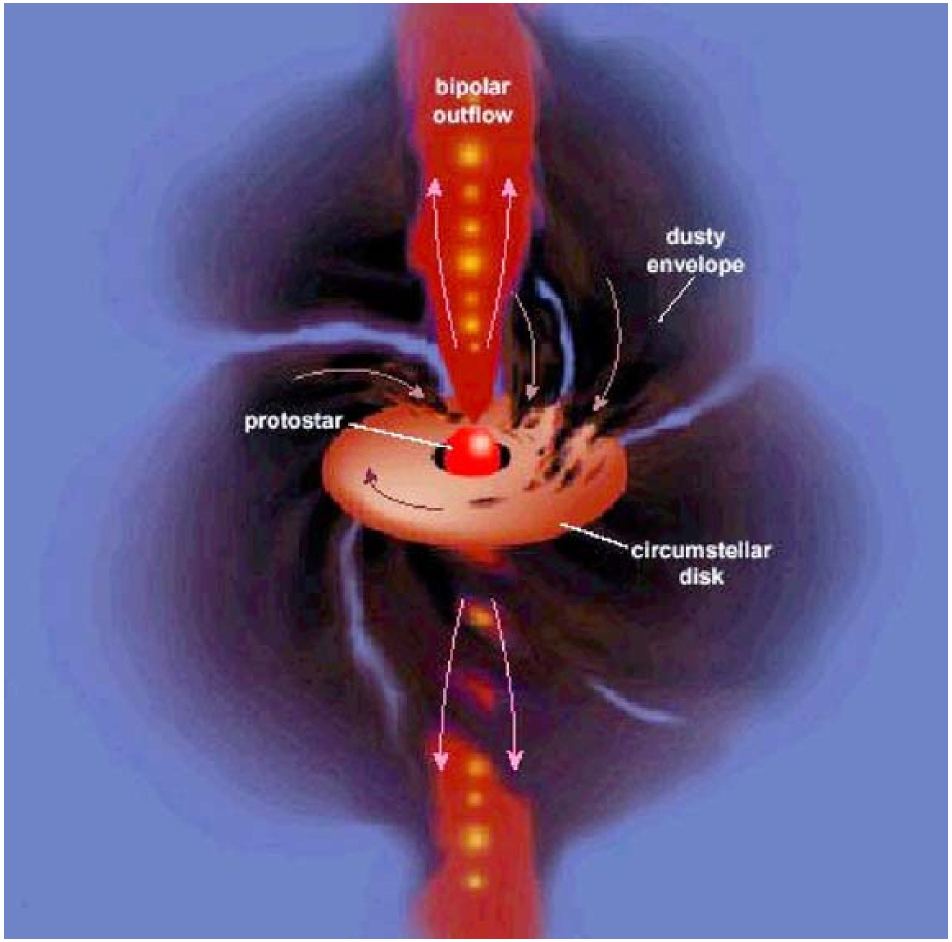


Recently formed hot stars can dissolve shroud with intense UV



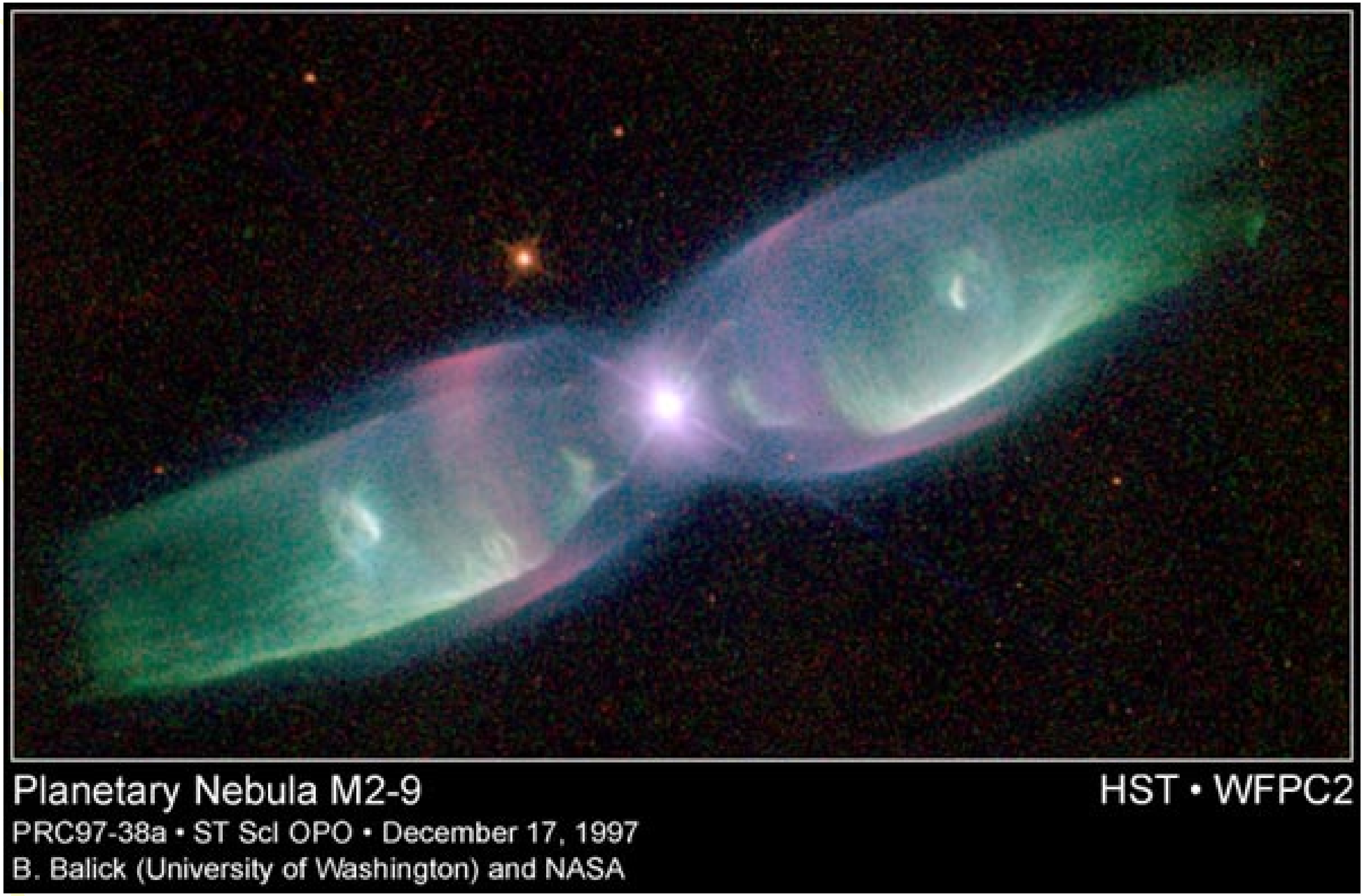
Disk and outflow are part of young star's development



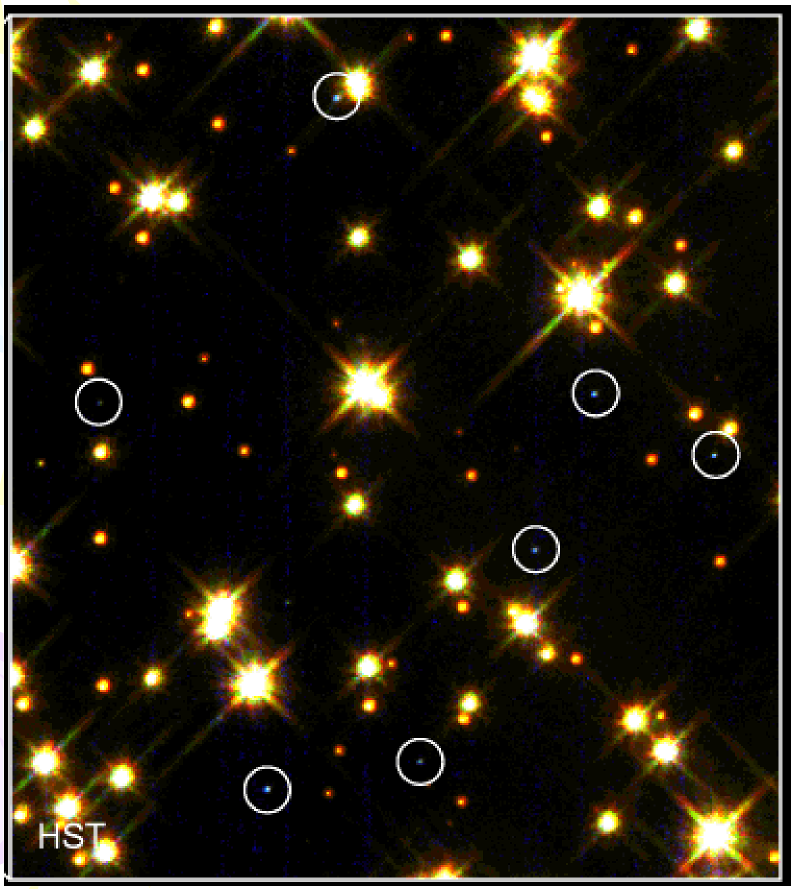


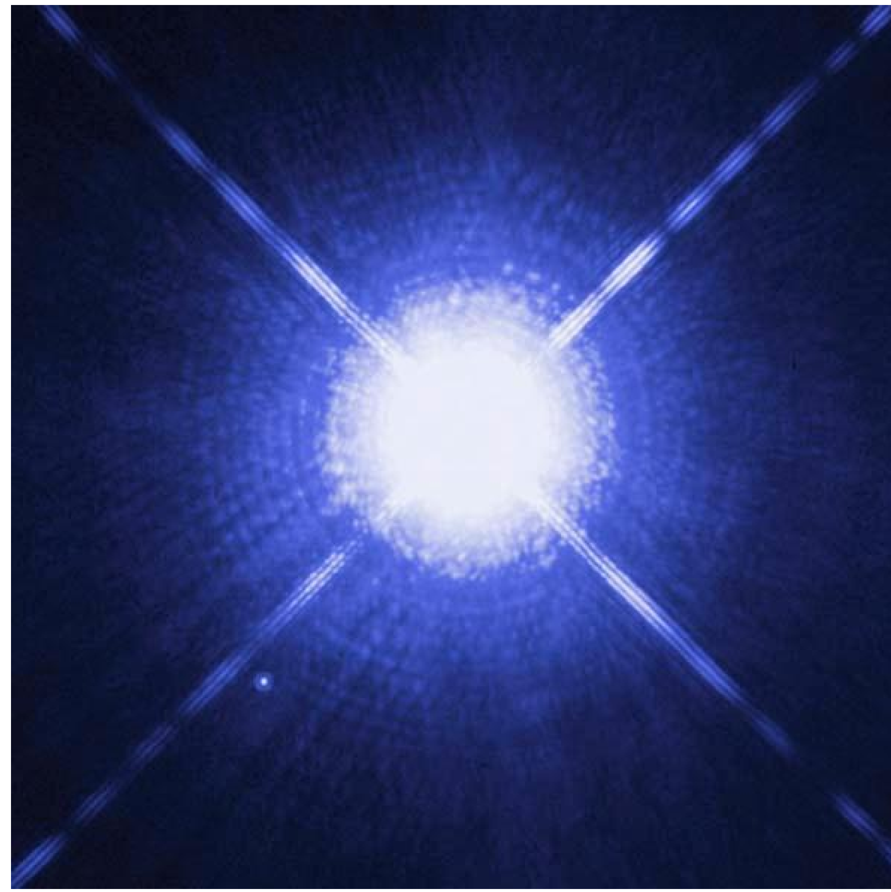
Hot, new stars excite large H II regions, like Orion

At the end of its life, a star may produce a planetary nebula...

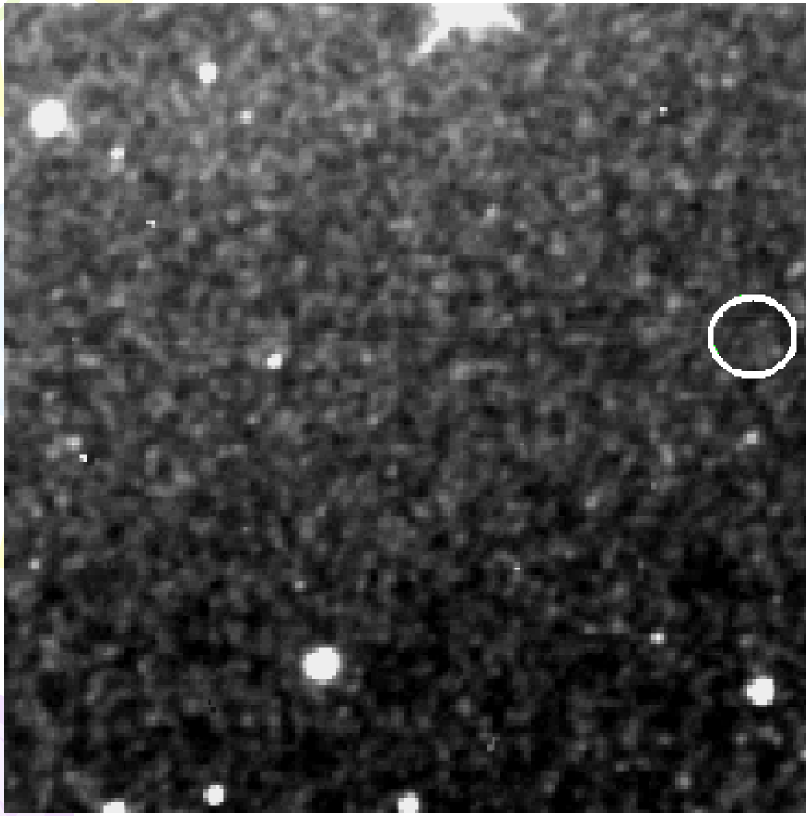


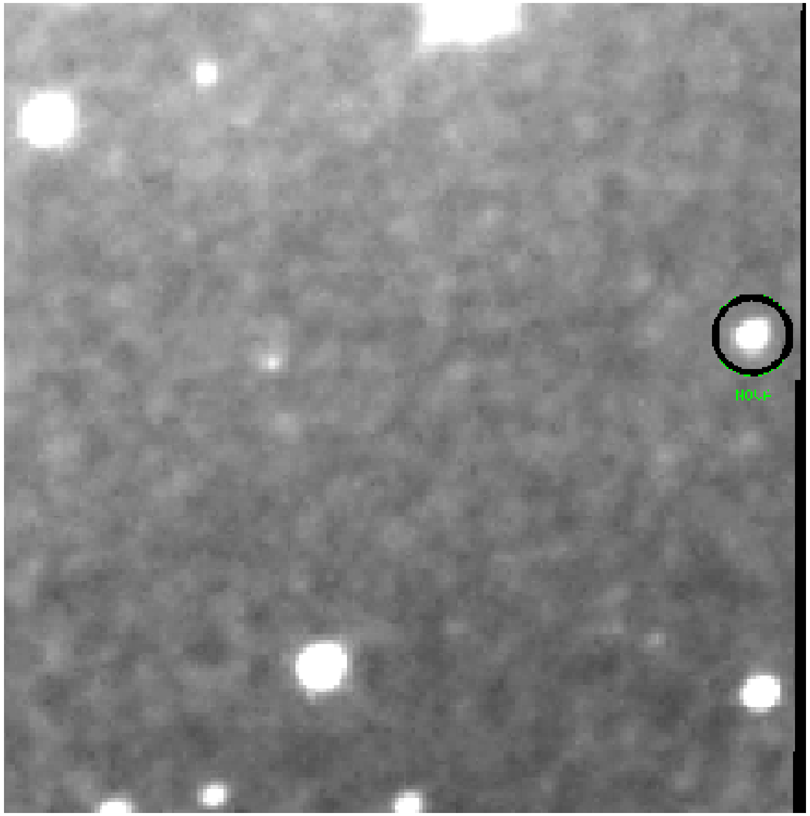
...on its way to becoming a white dwarf (WD)



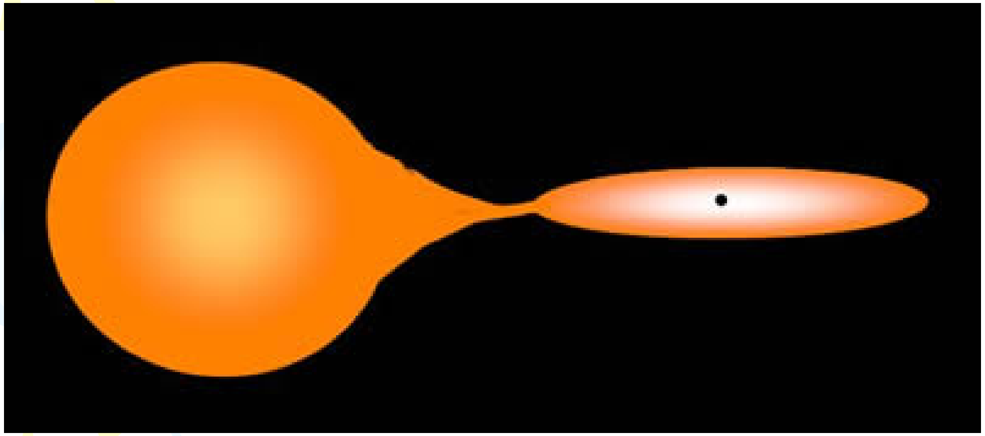


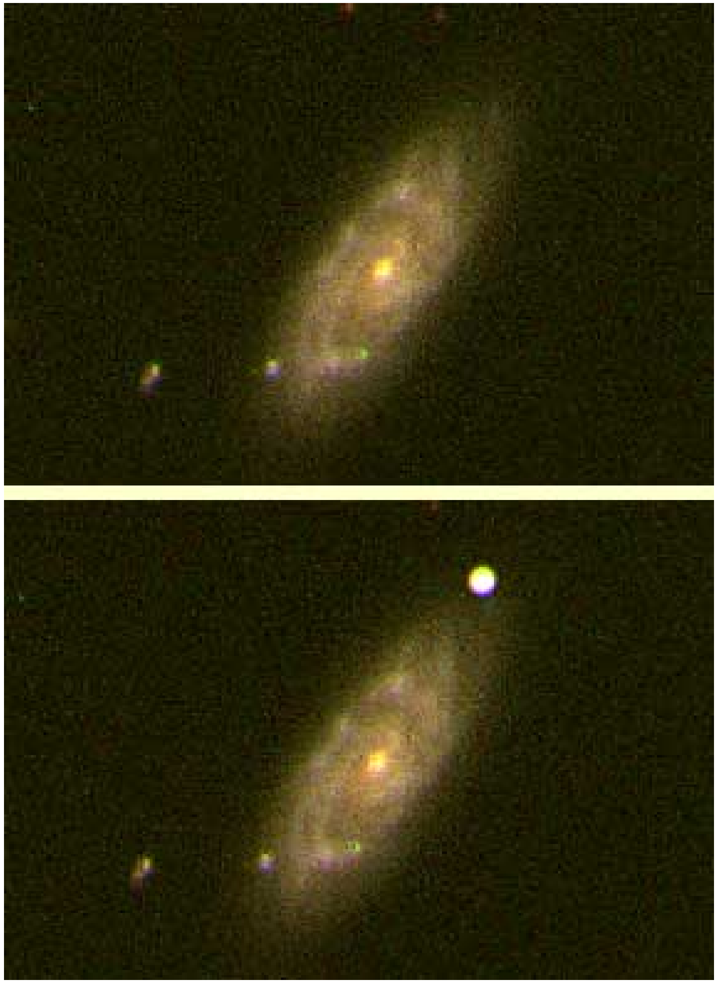
A WD with a companion may undergo nova outbursts





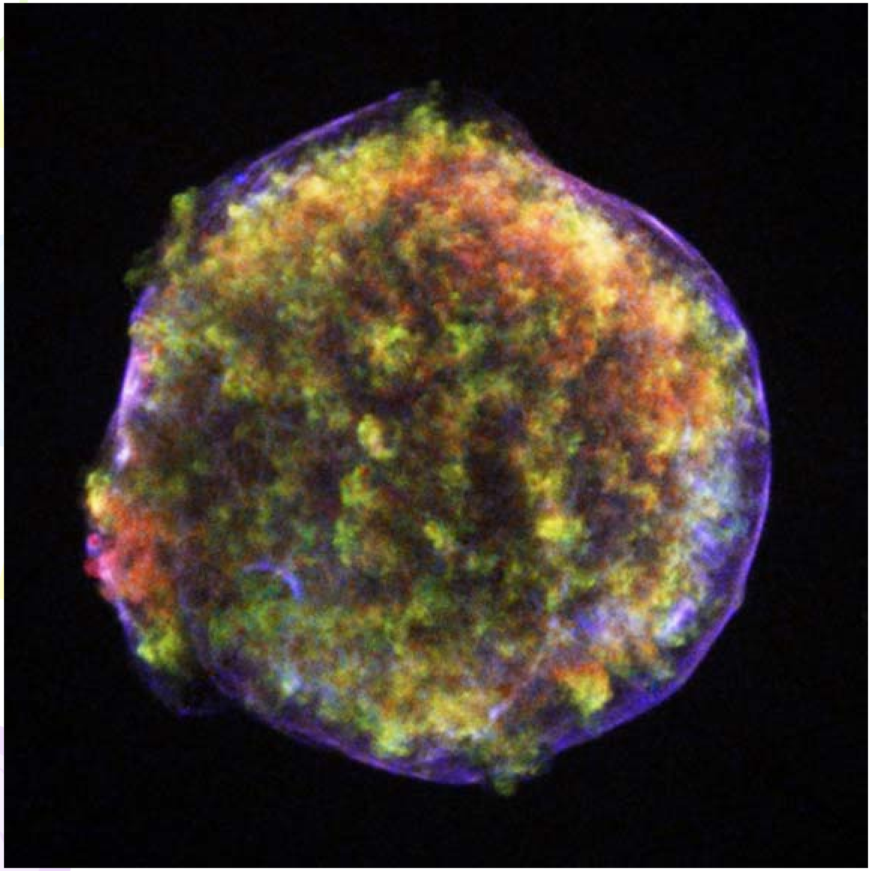
If enough material is accreted, the WD will explode

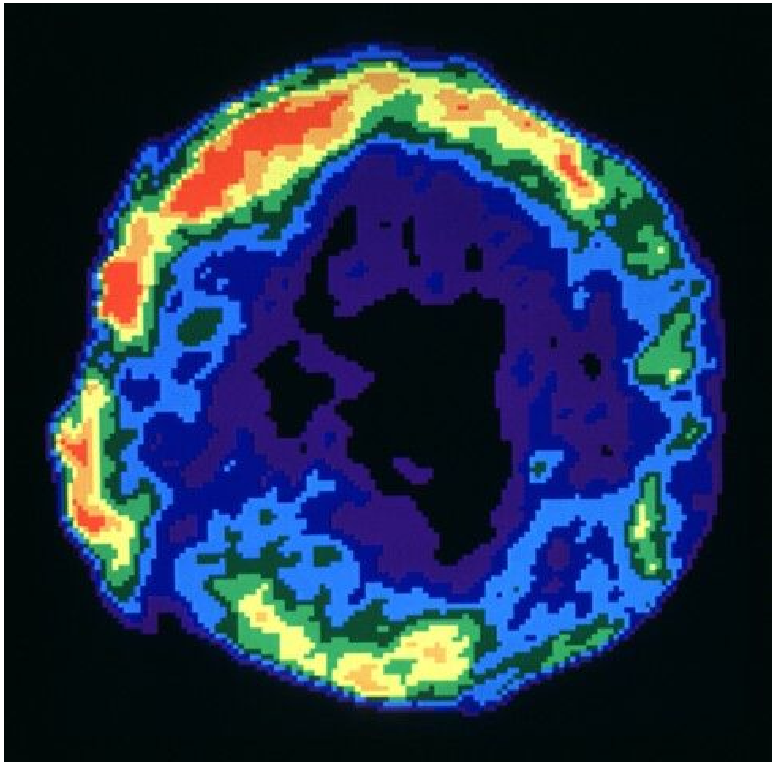




…as a Type Ia supernova (SN Ia)

This is the SNR from the "nova" seen by Tycho, 1572



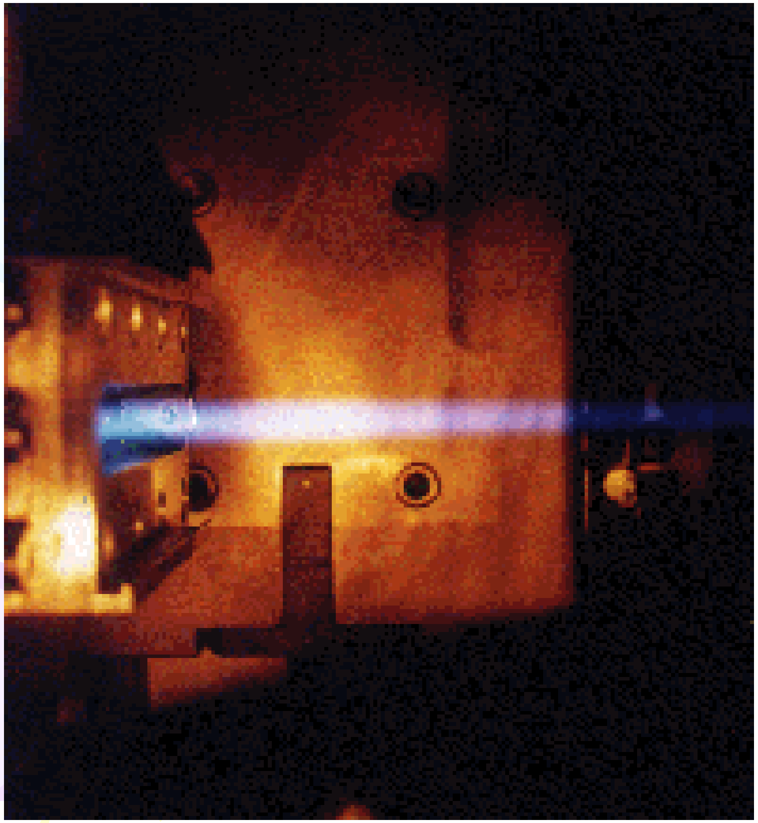


Chandra X-ray (left) & VLA radio map (right)

X-ray remnant of SN (probably Ia) observed in 1006 AD

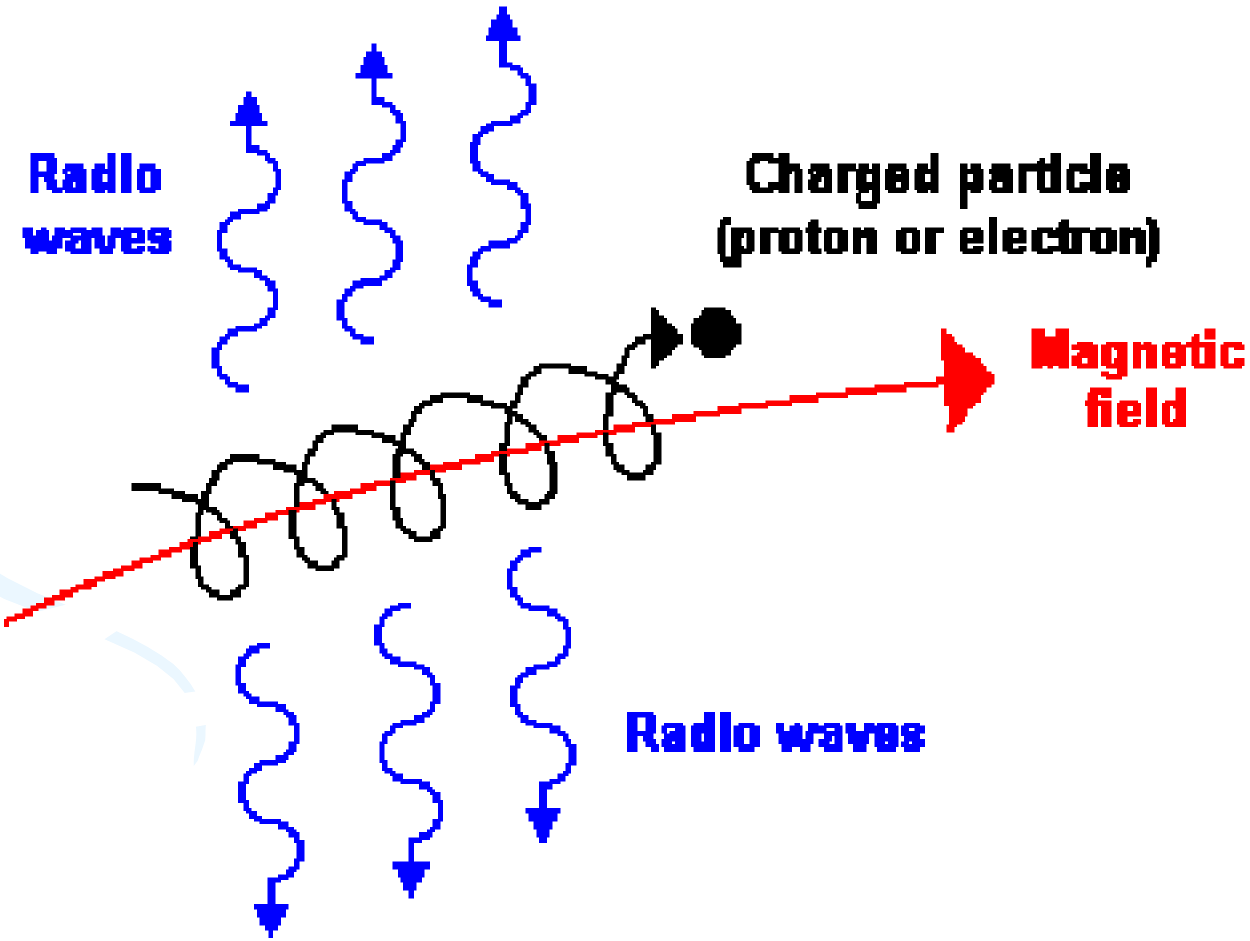
- X-rays mainly come from 10^6 K gas (red) heated in shock front
- Same shock boosts electrons to nearly *c*, to produce synchrotron emission (blue)
- Same synchrotron is cause of “nonthermal” radio emission

What is synchrotron radiation? First seen from accelerators

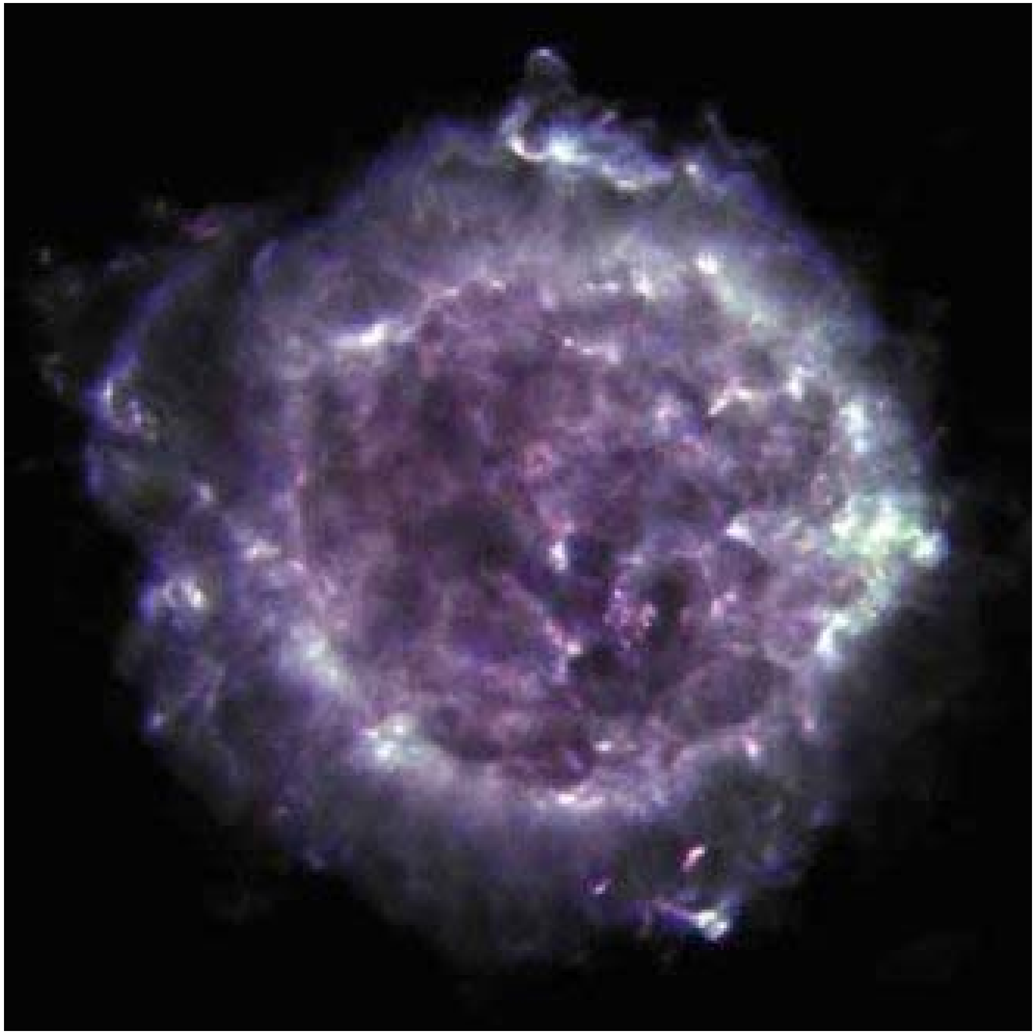


Synchrotron emission produces blue glow from Crab Nebula

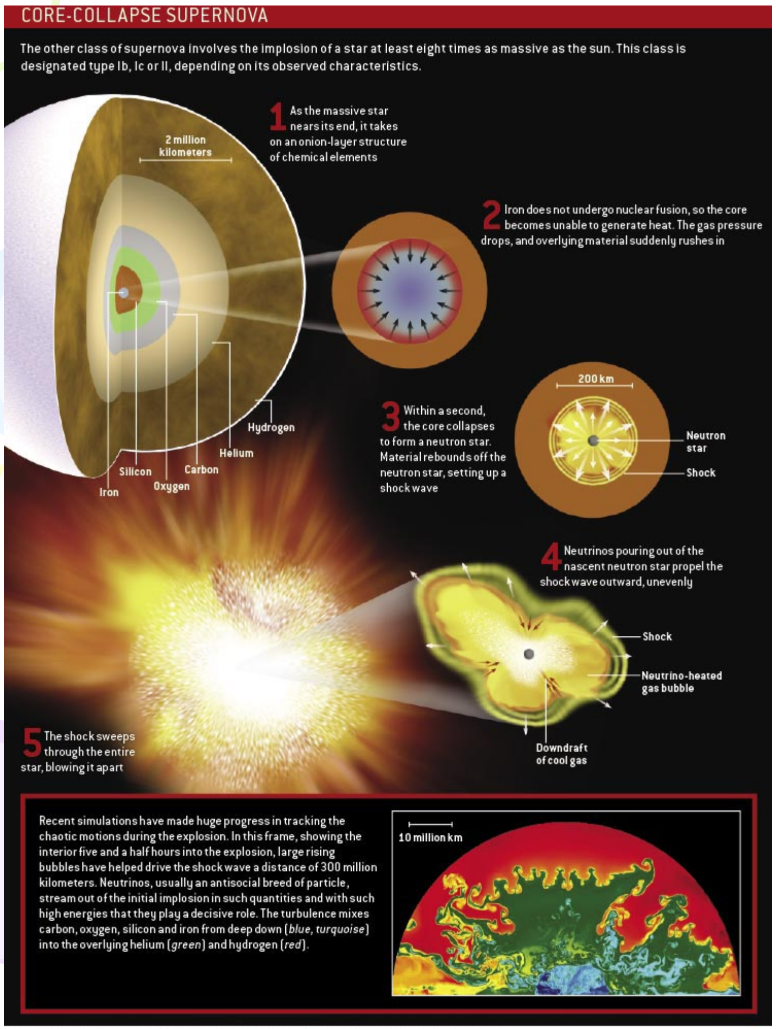
It is produced by high energy electrons in a magnetic field



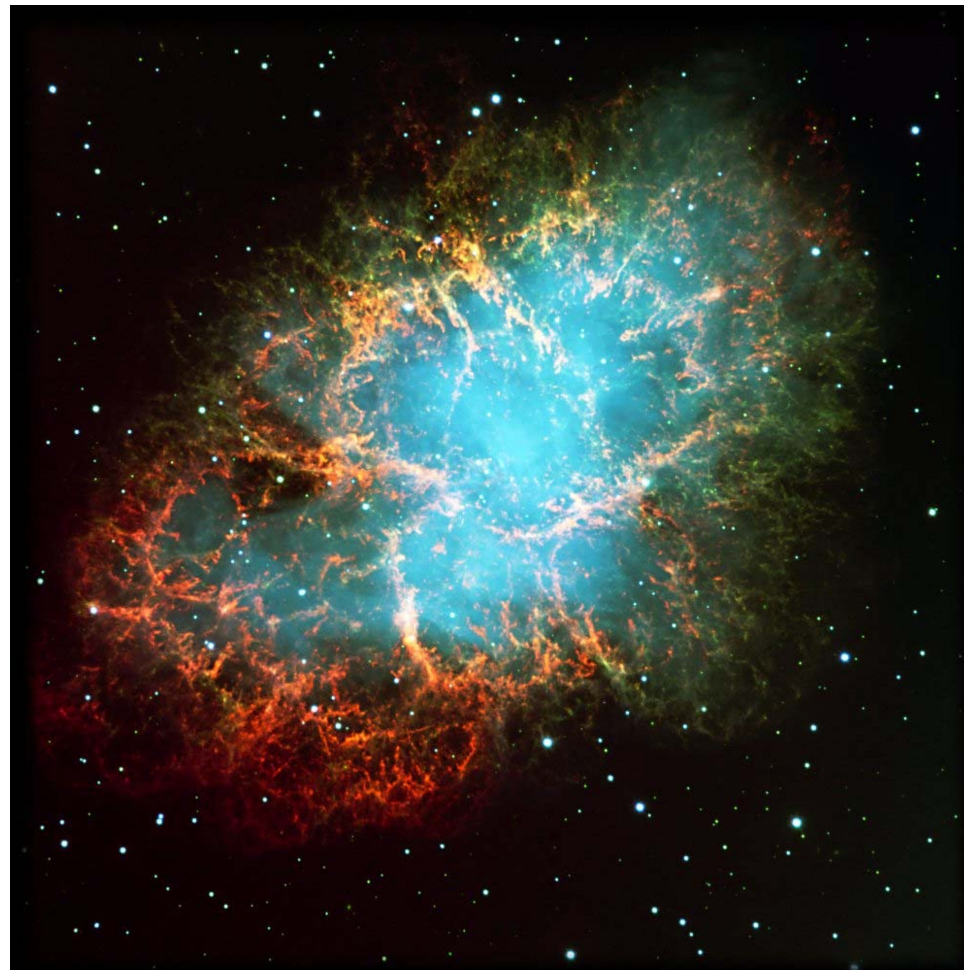
and is the most important source of radio emission in astronomy



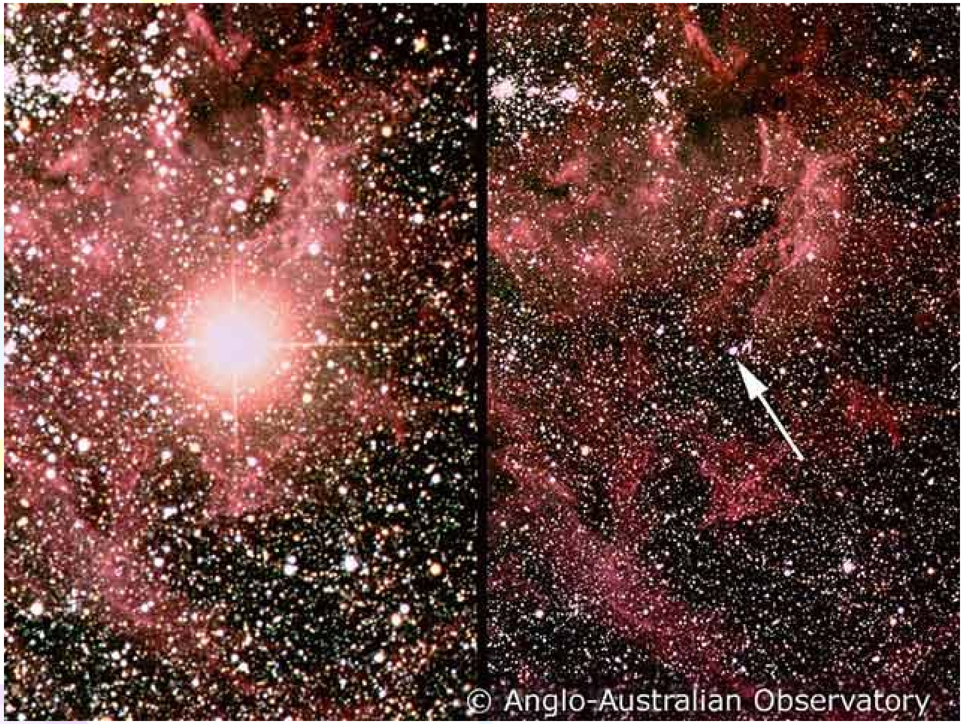
Ultimately a massive star will explode as a supernova

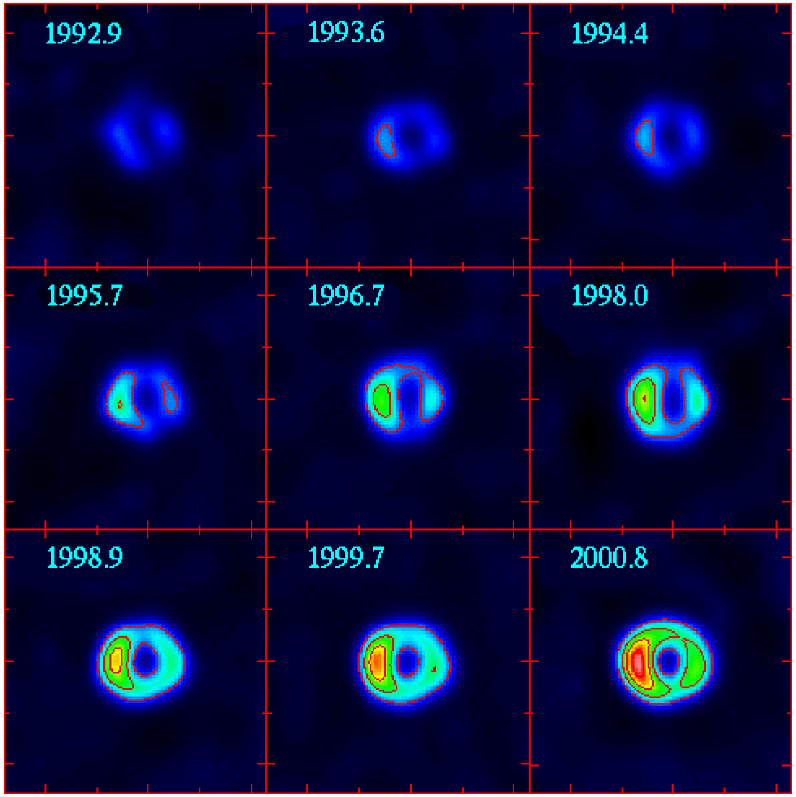


DON DIXON (*illustrations*); KONSTANTINOS KIFONIDIS *Max Planck Institute for Astrophysics* (*simulation*)



Might expect an explosion to produce a shell-like shock

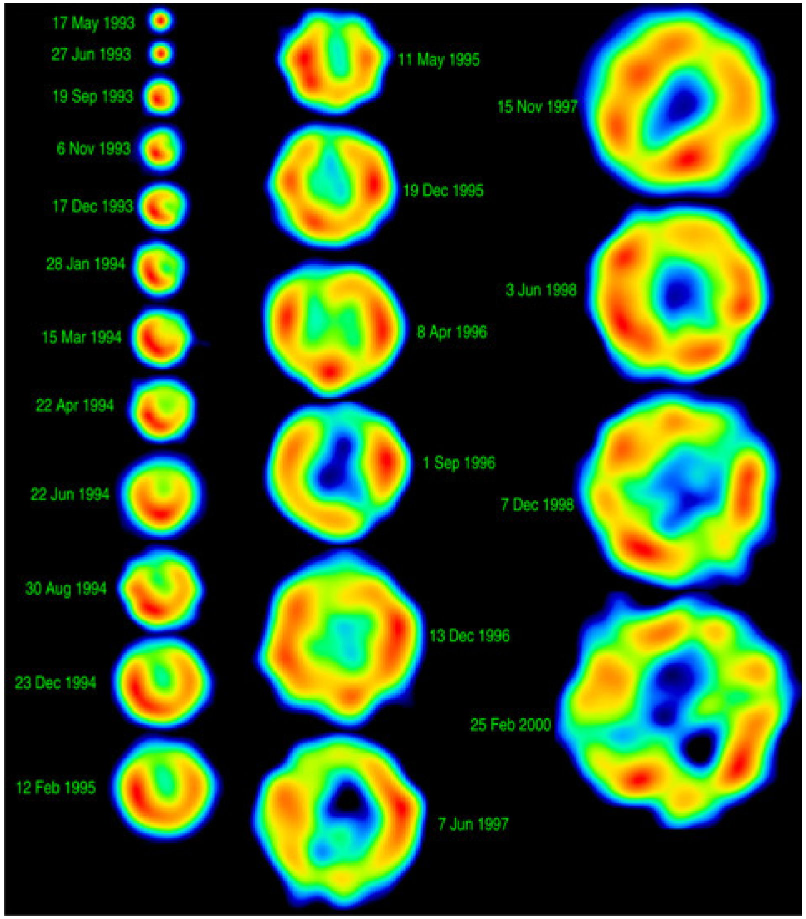




SN 1987A (Type II) & early radio shell

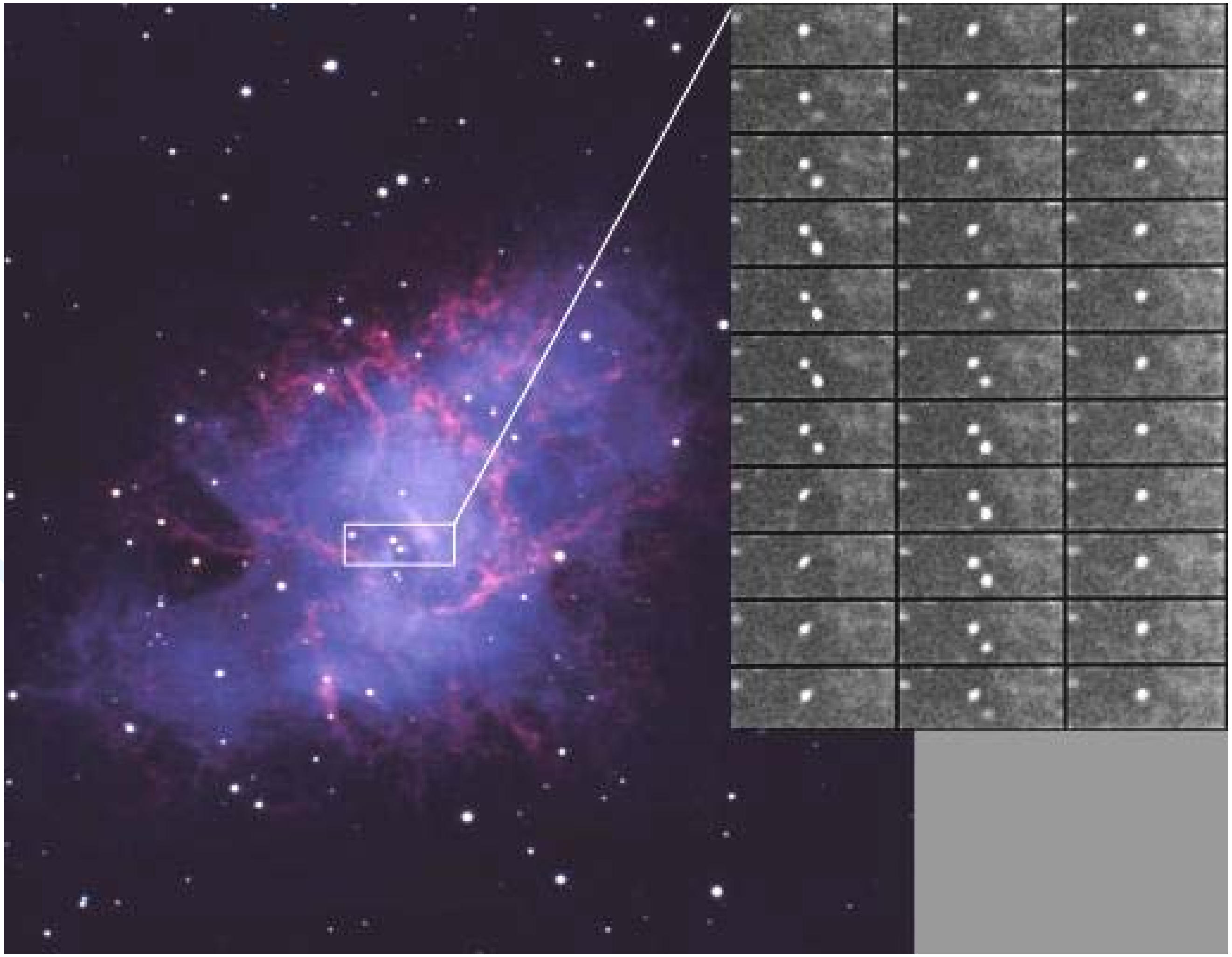
Also seen in the explosion of SN1993J in galaxy M81

- SN1993J was the explosion of a massive star
- Here we see evolution of the radio emission from the SN for first 7 years
- Notice circular shell shape, as expected from symmetry

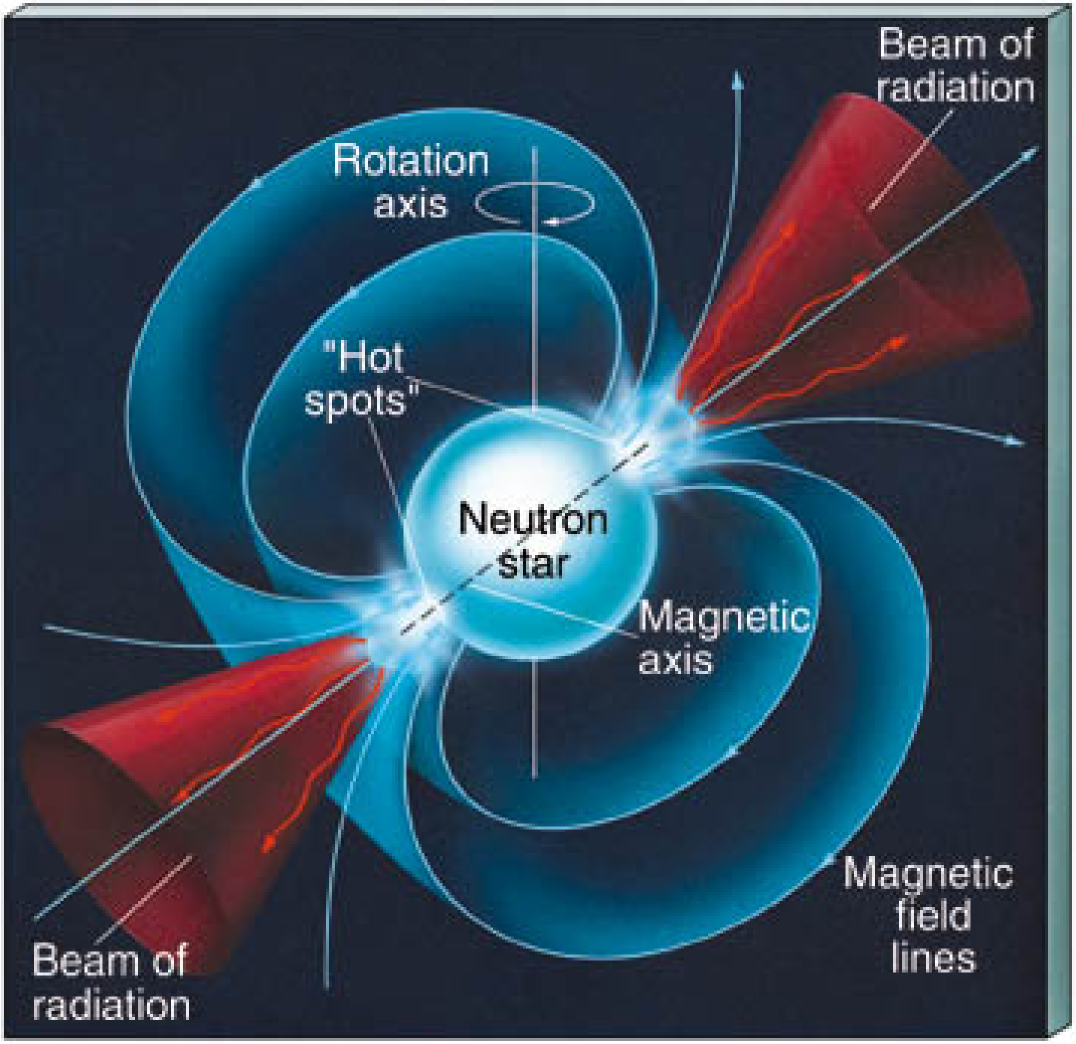


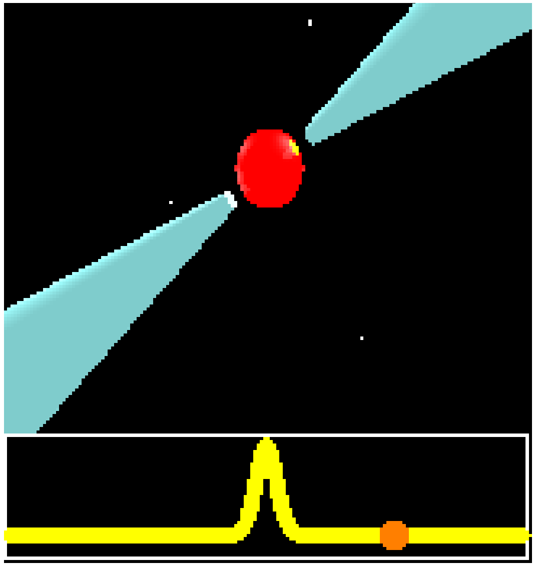
Two stars near center of Crab Nebula, one known to have nebula's motion

Crab: “center-filled” & influenced by energy from neutron star



Rotating magnetic field produces emission, seen every rotation period





Most kinds of galaxies have been detected as radio sources

- Spiral galaxies are generally weak radio emitters, but they contain much atomic hydrogen which can be observed for kinematical studies
- The most powerful radio emission is associated with giant elliptical galaxies
- Quasars are active nuclei in all kinds of galaxies

Different kinds of galaxies: spiral & elliptical most obvious

Main characteristics

- Spirals: grand spiral design

  Emission clouds, dust, young blue stars

  Central bulge, somewhat like elliptical

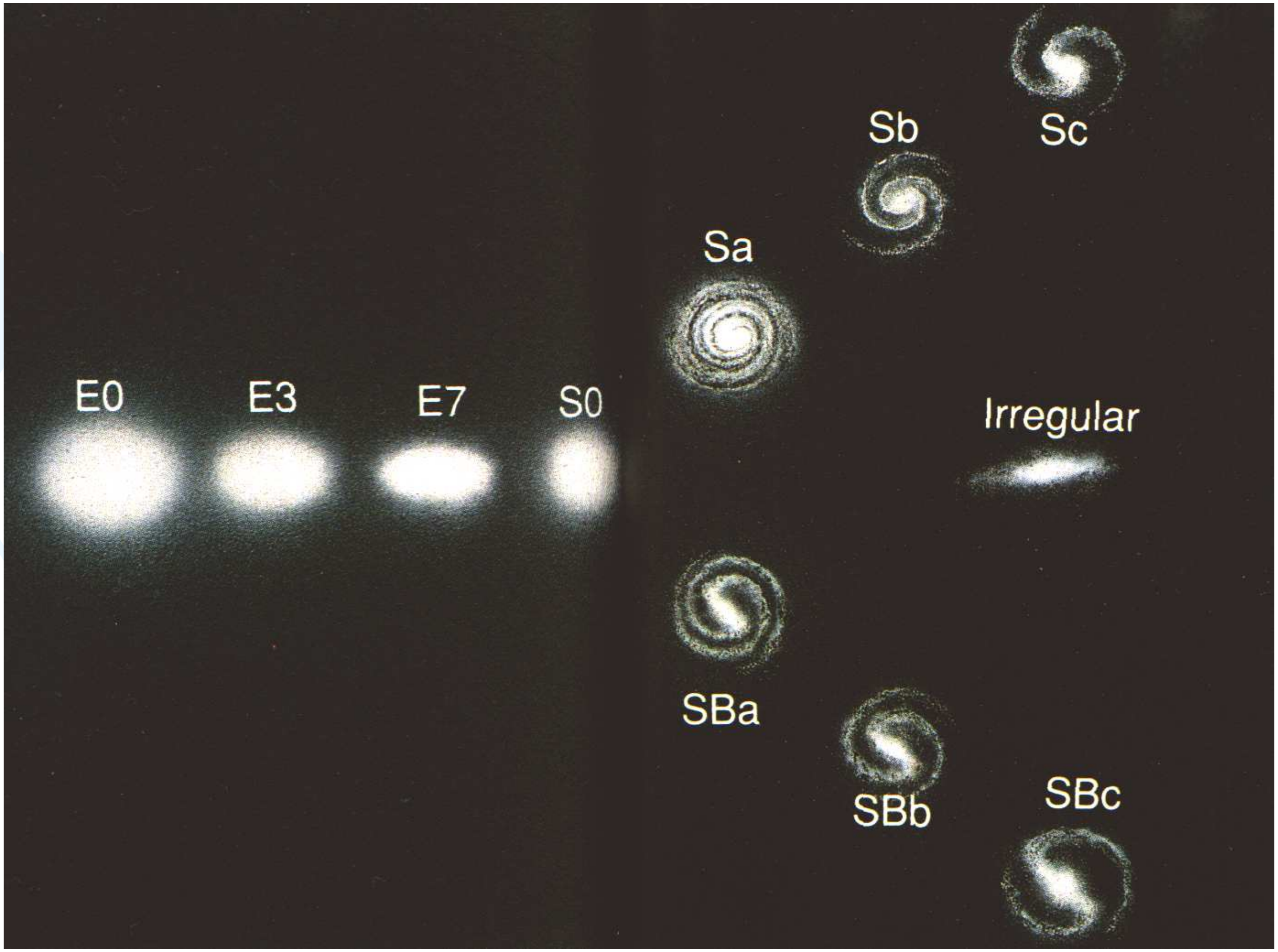
- Ellipticals: round or elliptical shape

  Amorphous, little or no dust

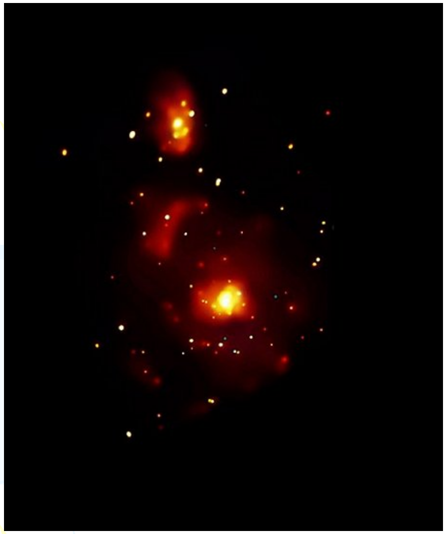
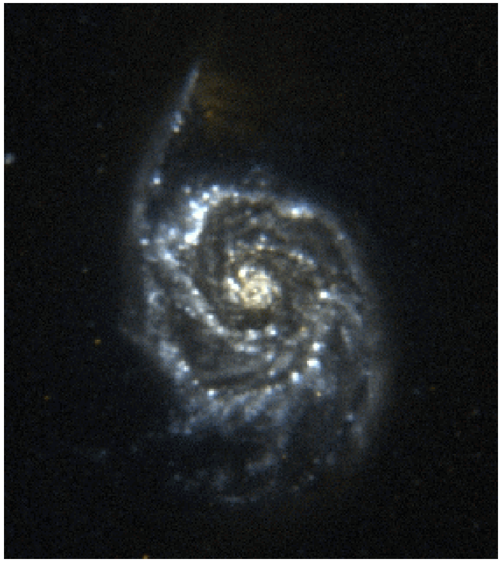
  No emission regions

  Old red stars

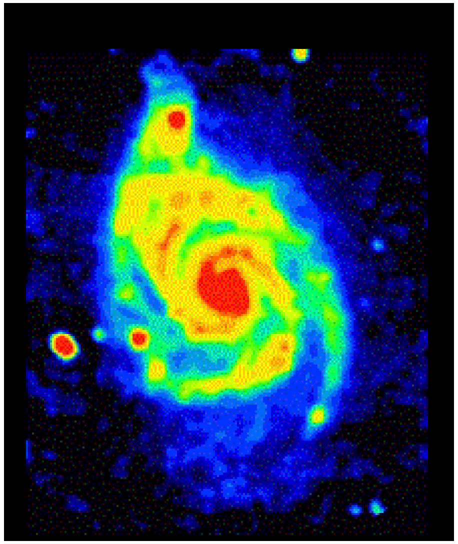
Hubble constructed a morphological sequence



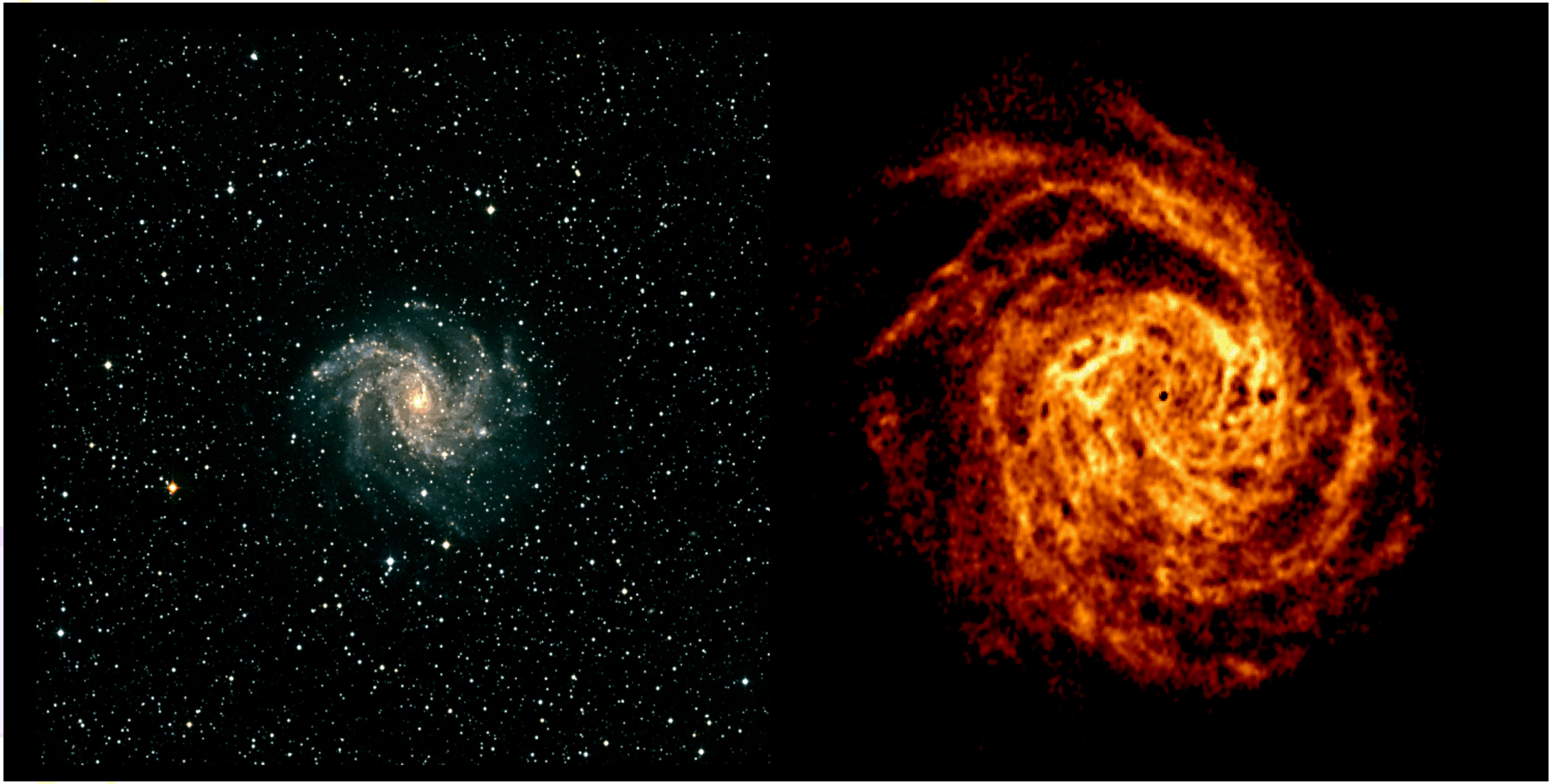
M51 in X-ray, UV, optical, near-IR, mid-IR & radio 20 cm

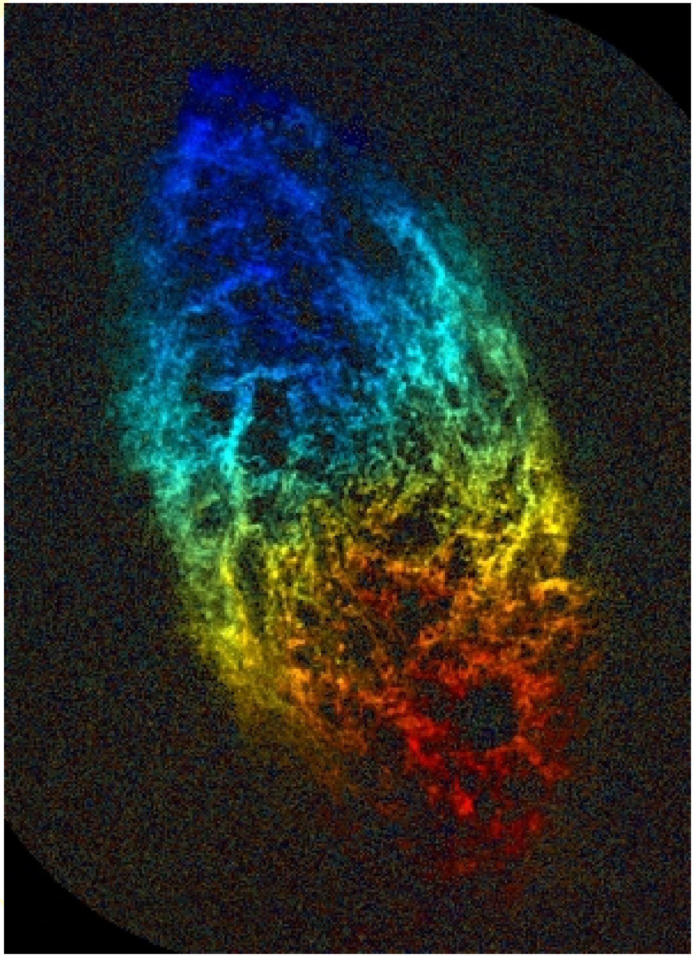




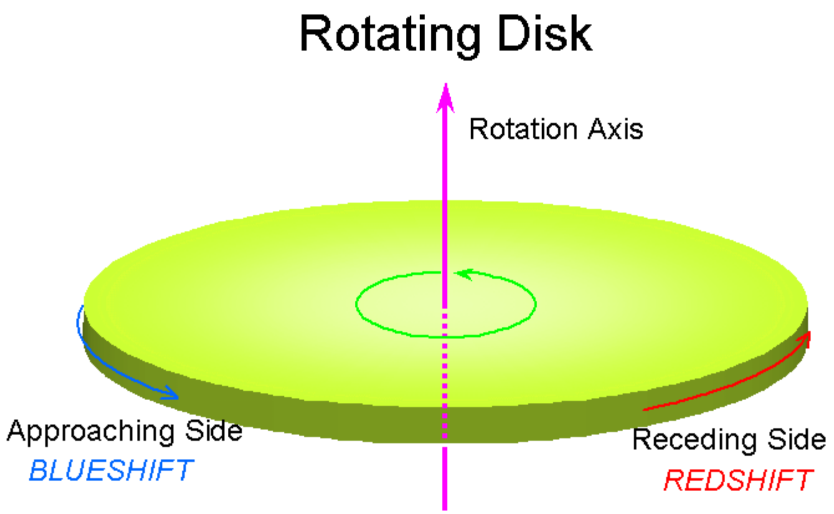
NGC 6946 – note how much larger the HI disk is than optical

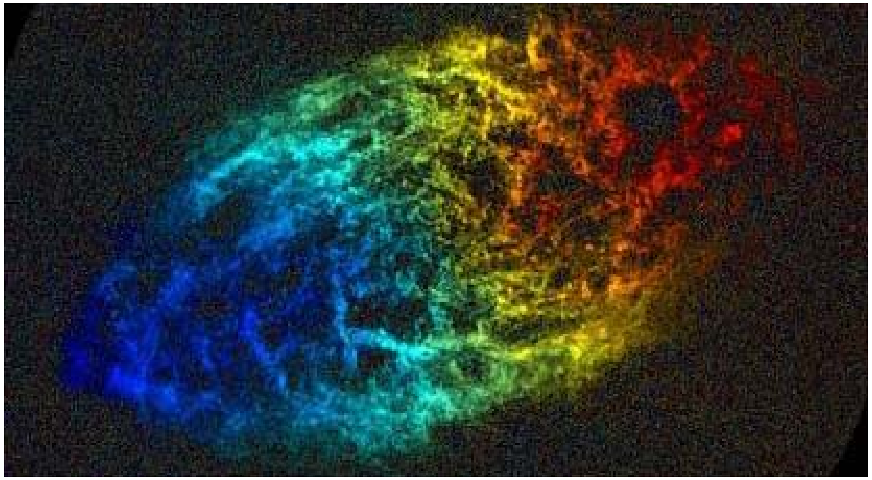


Rotation in many spirals from 21 cm HI mapping (M33)



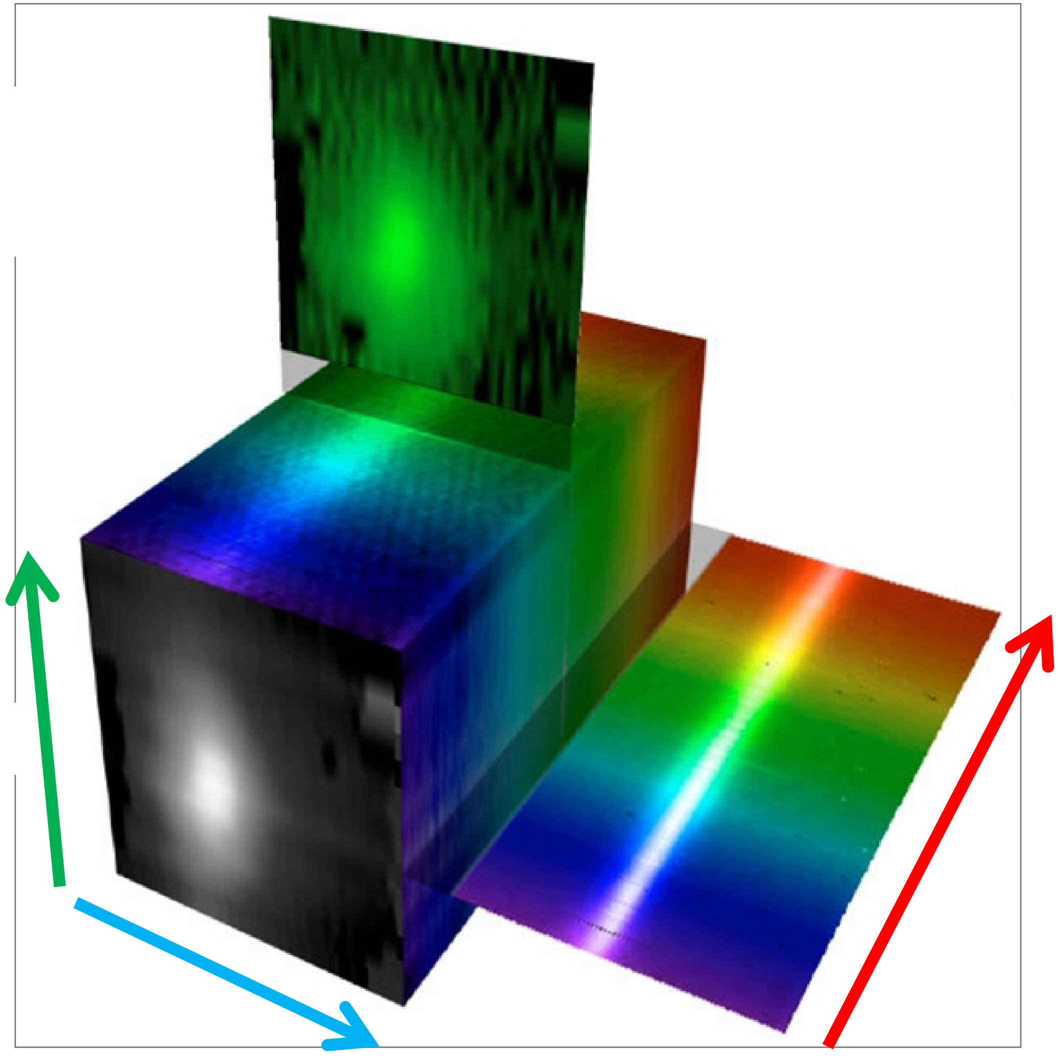
Doppler shift in rotating disk viewed obliquely: what we see



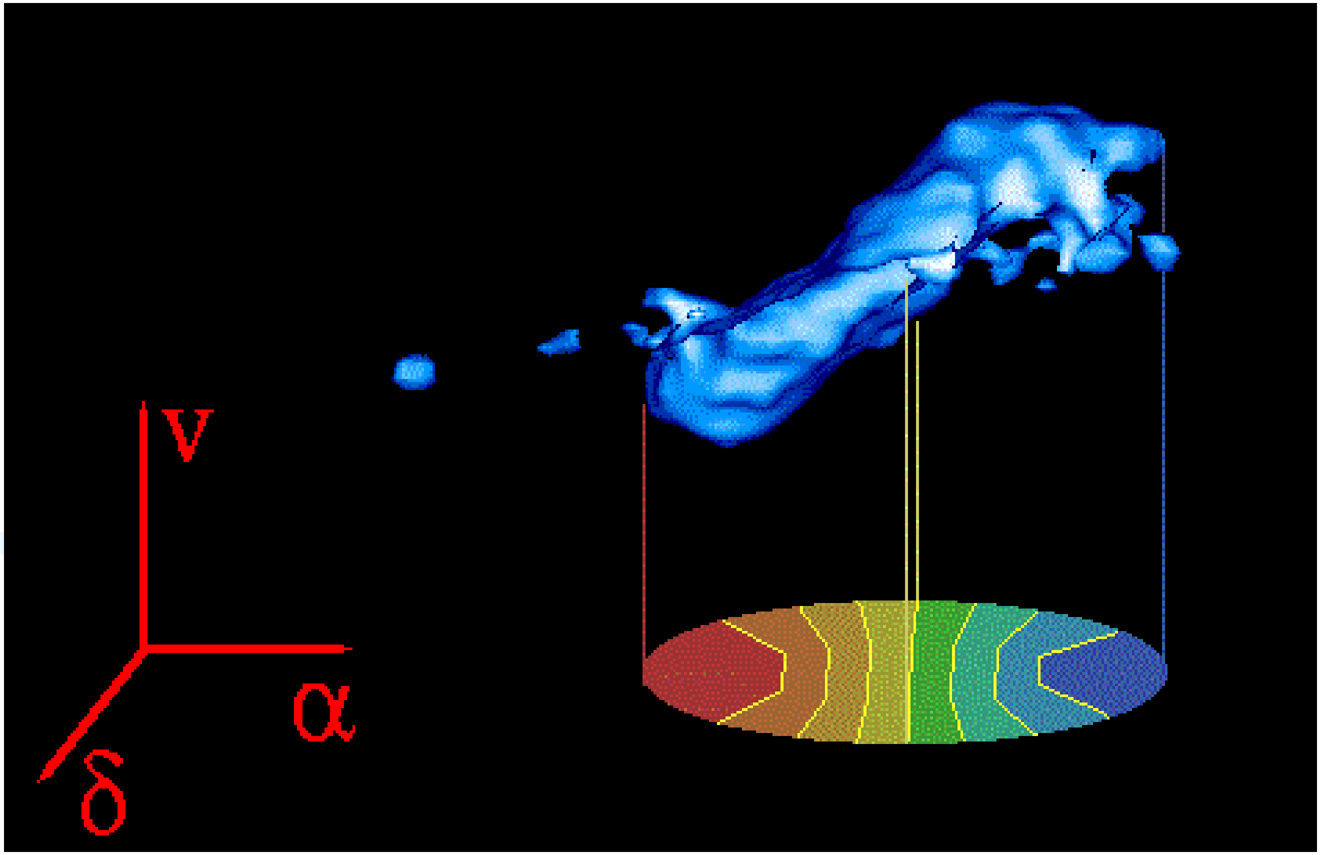


- We can only see motion of gas along line of sight
- Can determine true rotation speed if tilt known
- From speed, estimate galaxy mass (Newton's laws)

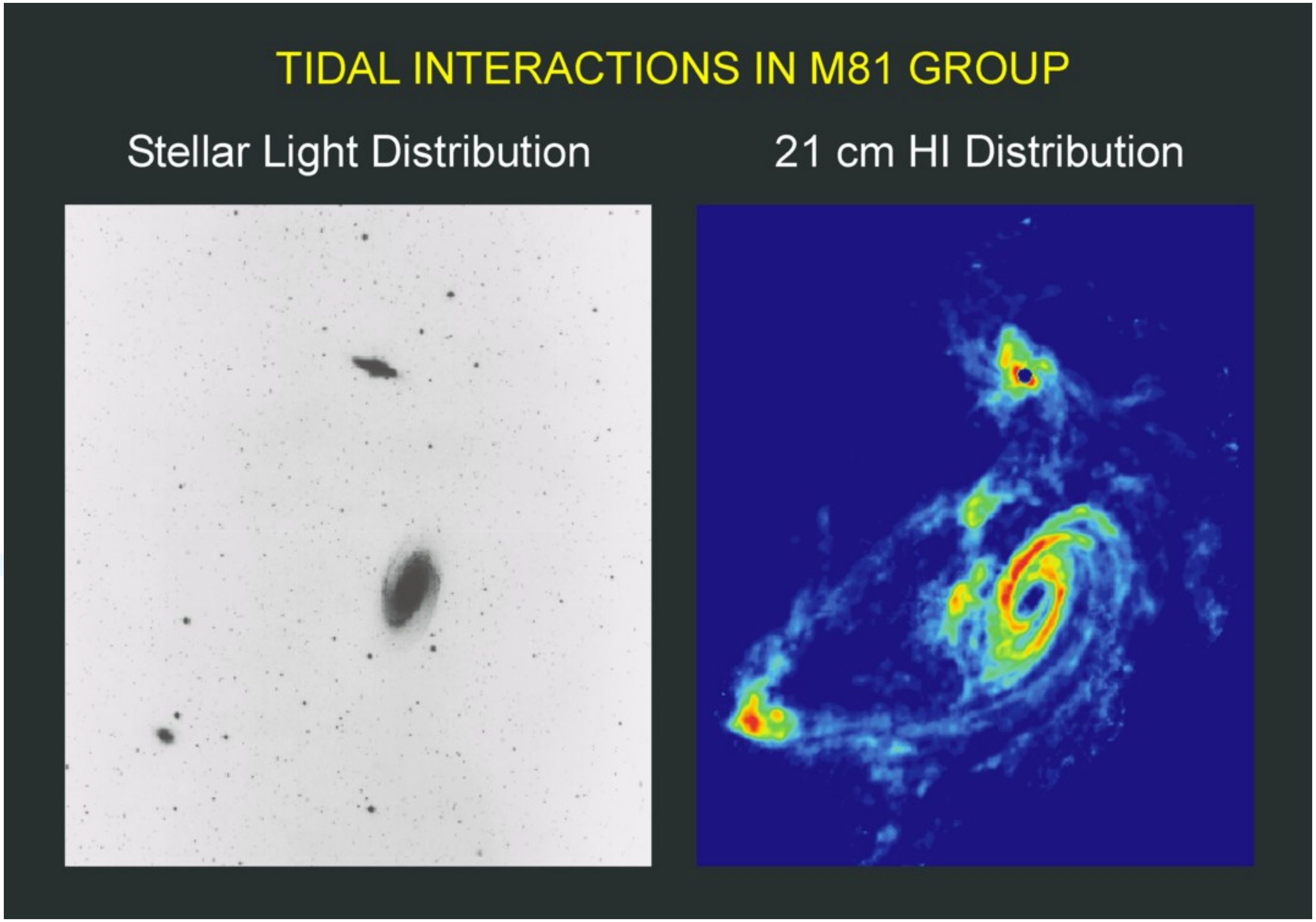
How do we present our map? As a “data cube” in *x*, *y* & *v*



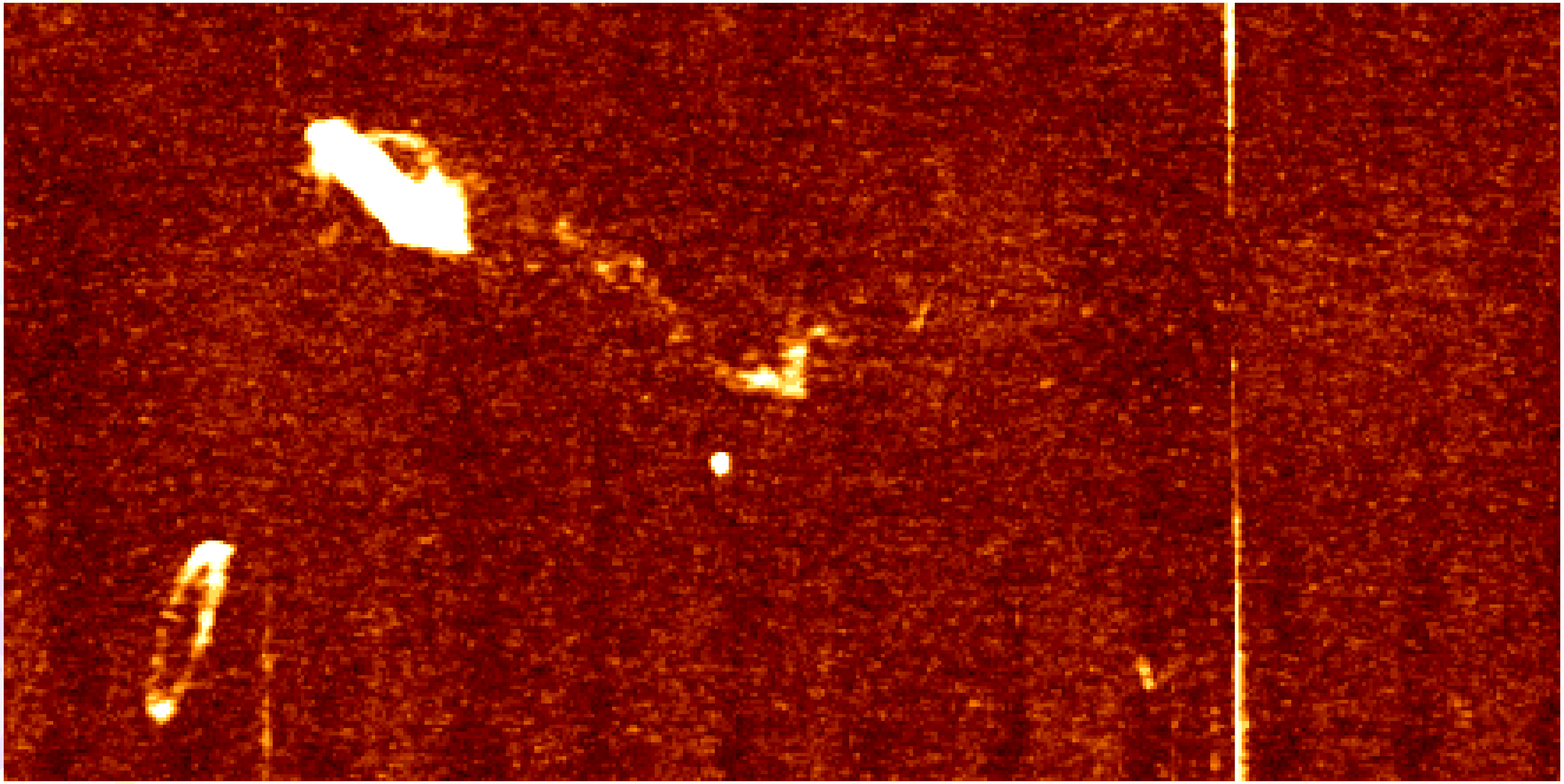
HI in dwarf galaxy, and how we visualize 3D data “cube”



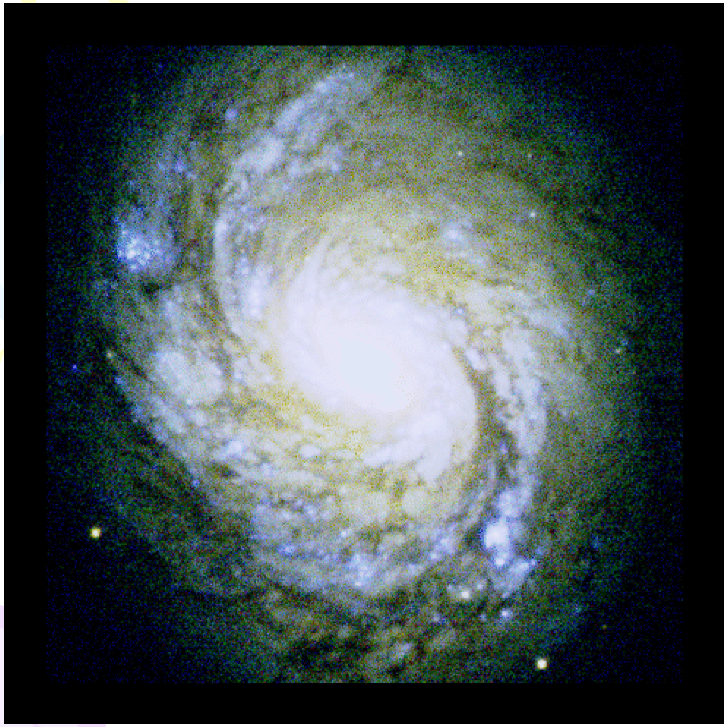
M81 group: much HI showing interactions between galaxies

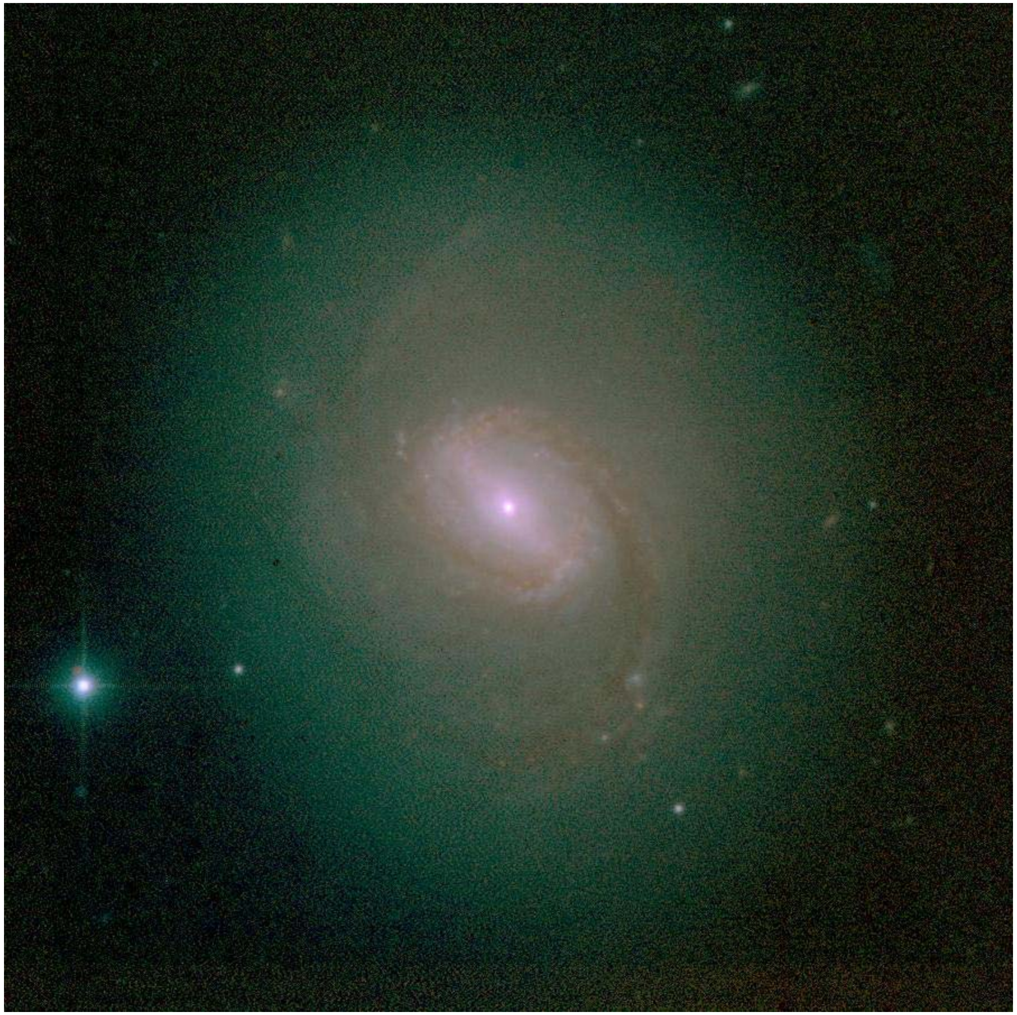


Here we see a rotating "data cube" of 21 cm emission

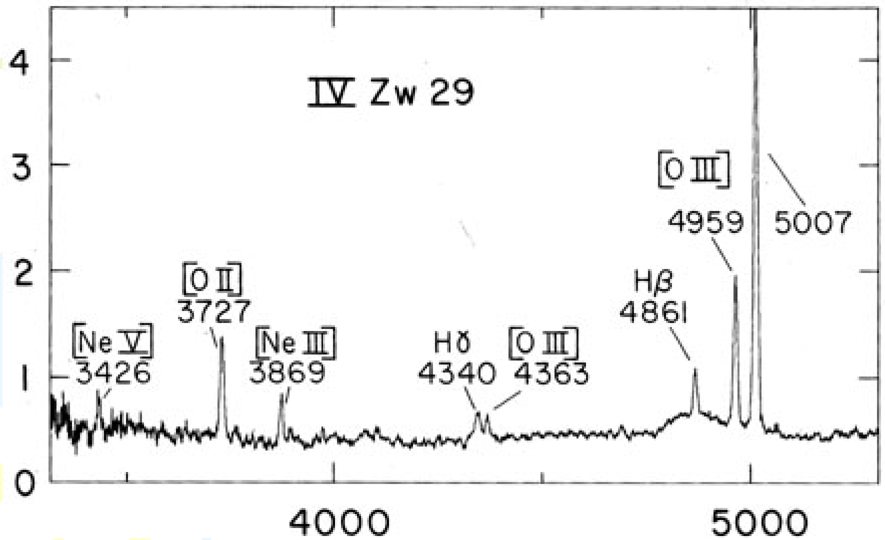


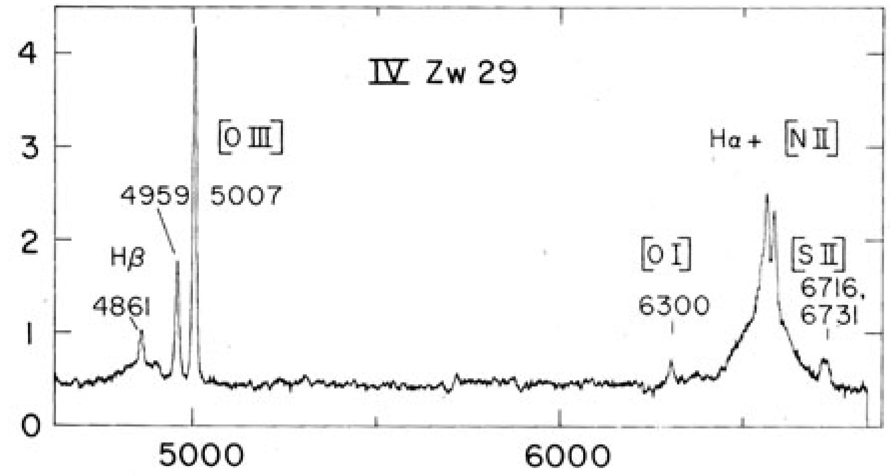
C. Seyfert found several galaxies with "star-like" nuclei & emission lines





Spectrum of the Seyfert galaxy IV Zw 29



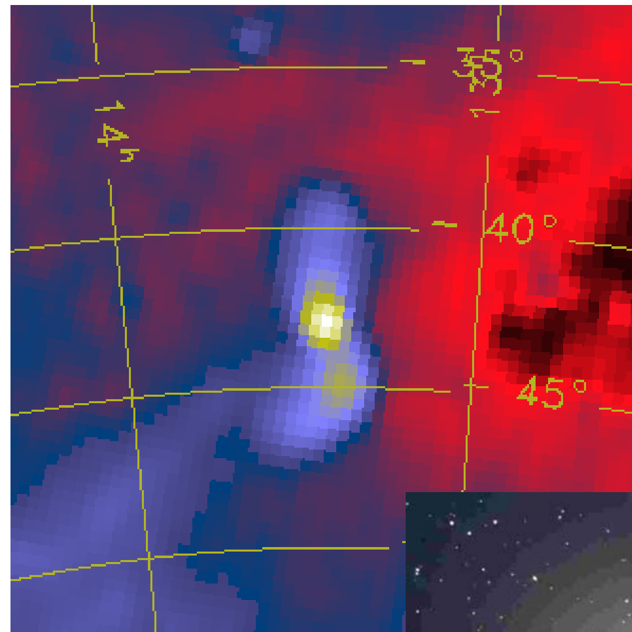


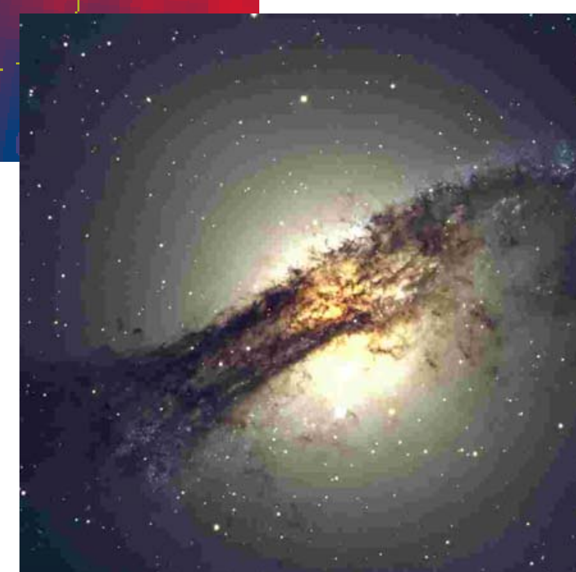
- It is not one of Seyfert's original galaxies, but shows typical emission lines
- Note narrow and broad lines of hydrogen, and narrow forbidden lines, [O I], [S II], etc.

Study of active galaxies gets underway with radio sources

Two key discoveries:

- Identification of the strong southern radio source Cen A with a nearby bright galaxy NGC 5128
- Detection of large radio lobes north and south of galaxy



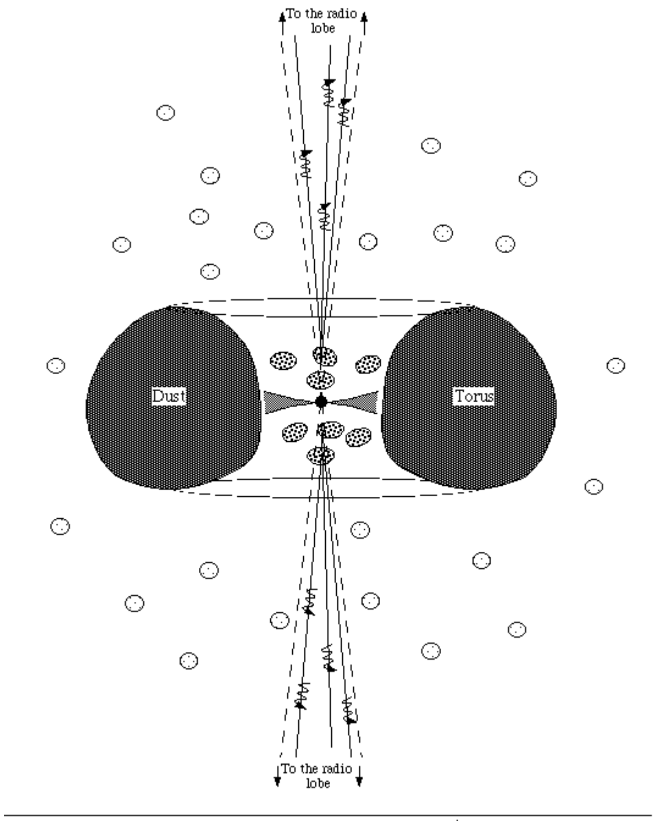


Around 1970, there were two significant developments

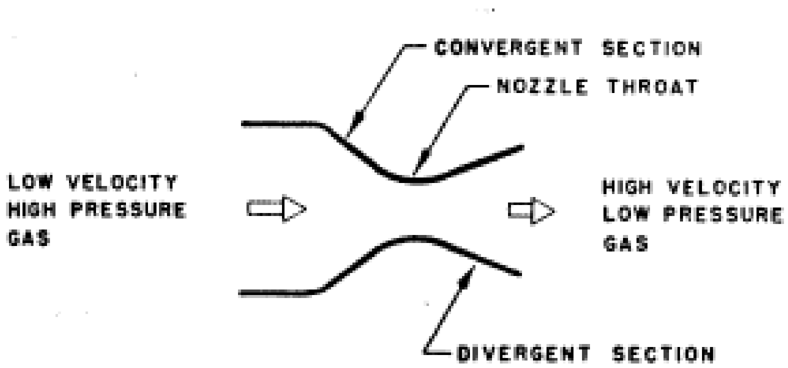
- The possibility that black holes (BHs) might be present in galaxy nuclei began to be taken seriously
- R. Kerr had shown (1963) that energy could be extracted from a spinning BH
- BHs quickly became popular in astronomy

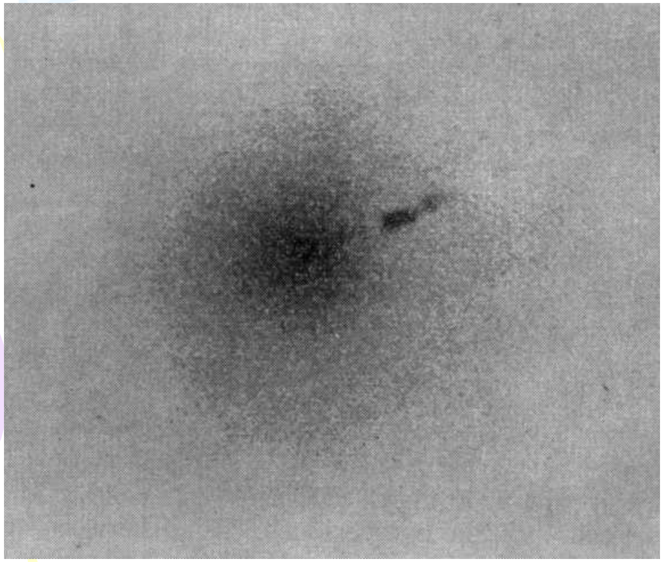
The second development concerned energy transport

- R. Blandford & M. Rees developed a model in which high energy gas in galaxy center, held in place by disk pressure, breaks out of disk
- The gas then squirts out in 2 opposite directions perpendicular to the disk, transporting energy far from nucleus



The jets would be high speed, and nearly lossless

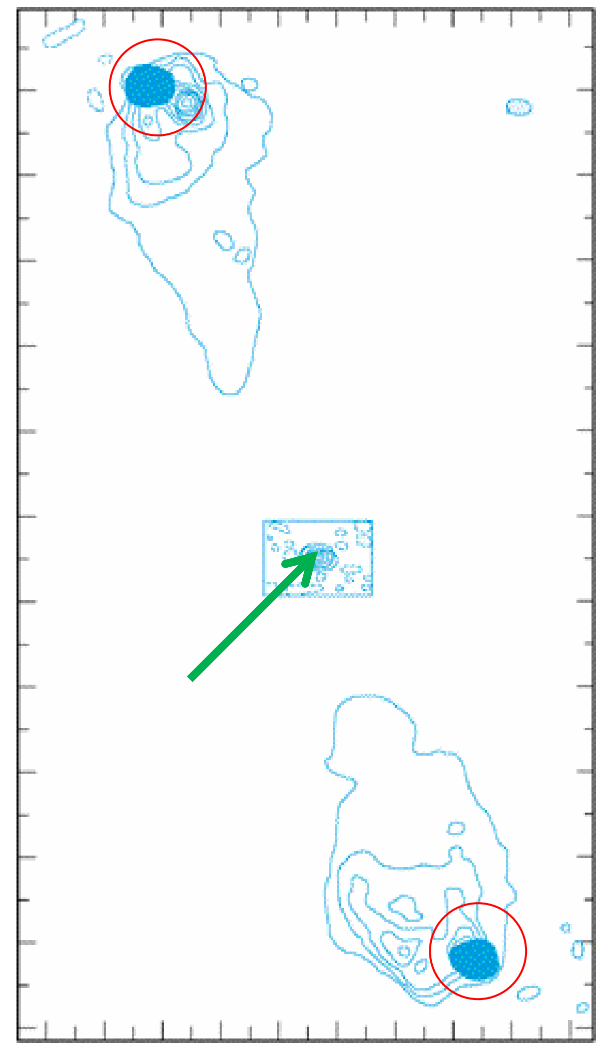




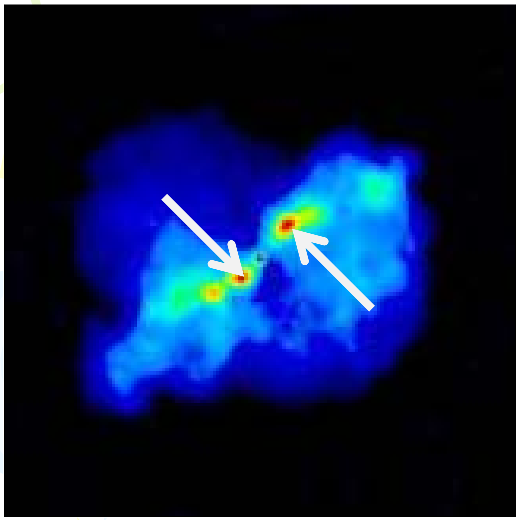
- Blandford & Rees argued that where the gas broke through, a natural “de Laval nozzle” would form
- The jet in M87 was known, but jet-like features were rarely seen in radio galaxies
- An efficient (lossless) jet would be invisible

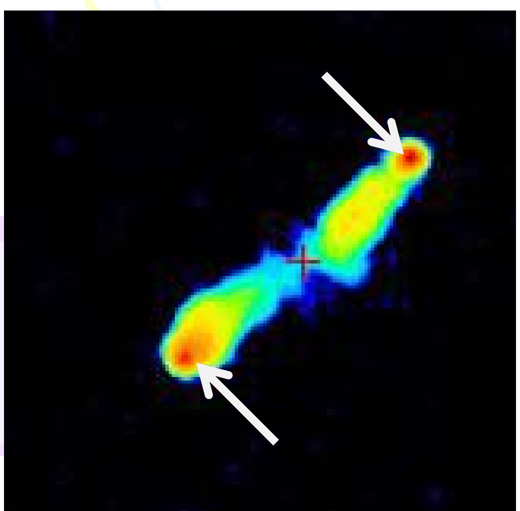
Observationally, there were sharper images of Cyg A

- In the US and UK, high resolution maps showed compact bright spots in the lobes
- Here is a Cambridge map of Cyg A; note nucleus
- Ram pressure would not be able to confine such compact “hot spots”
- But they could be the tips of jets



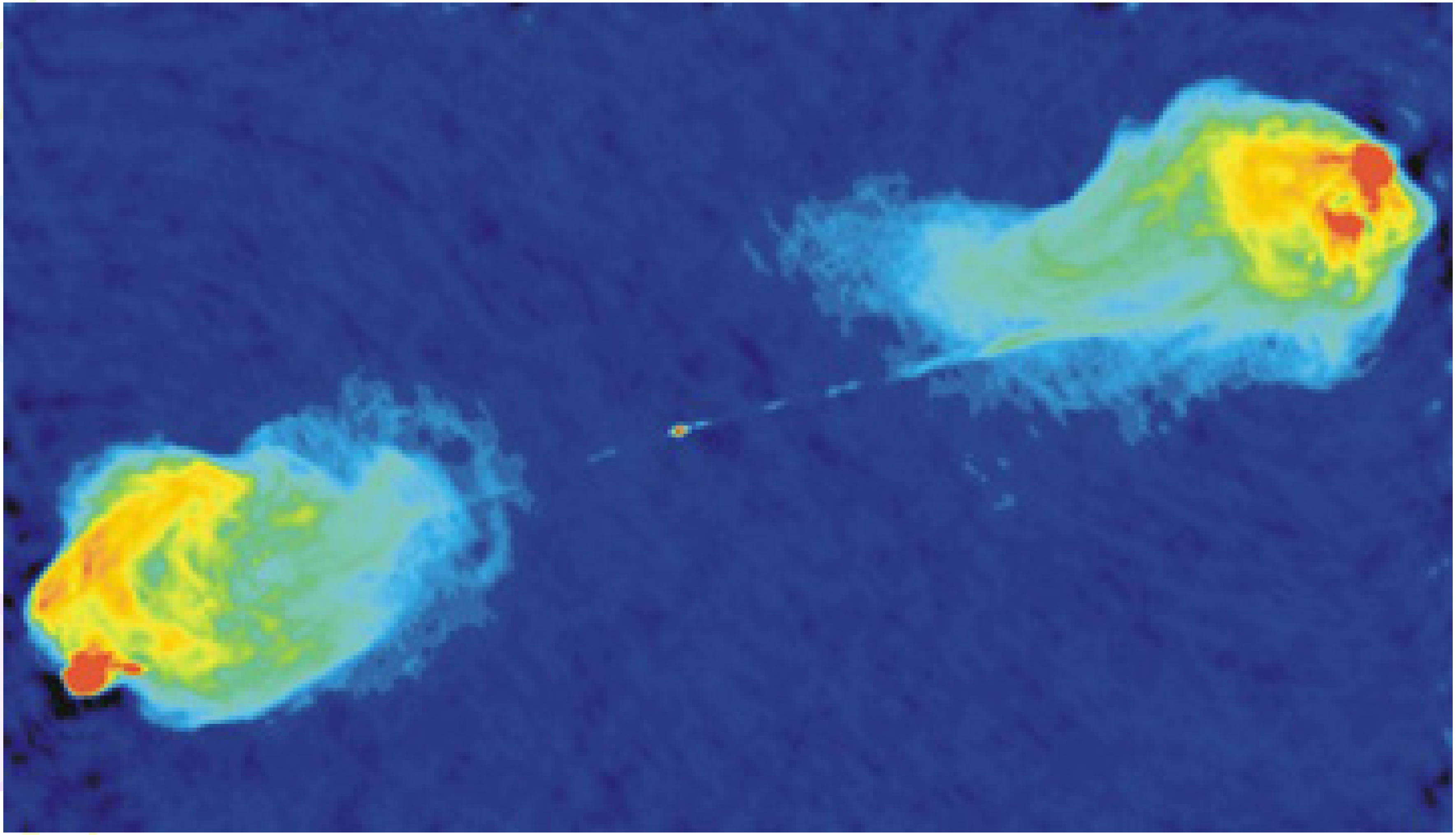
Cambridge radio astronomers Fanaroff & Riley: classification



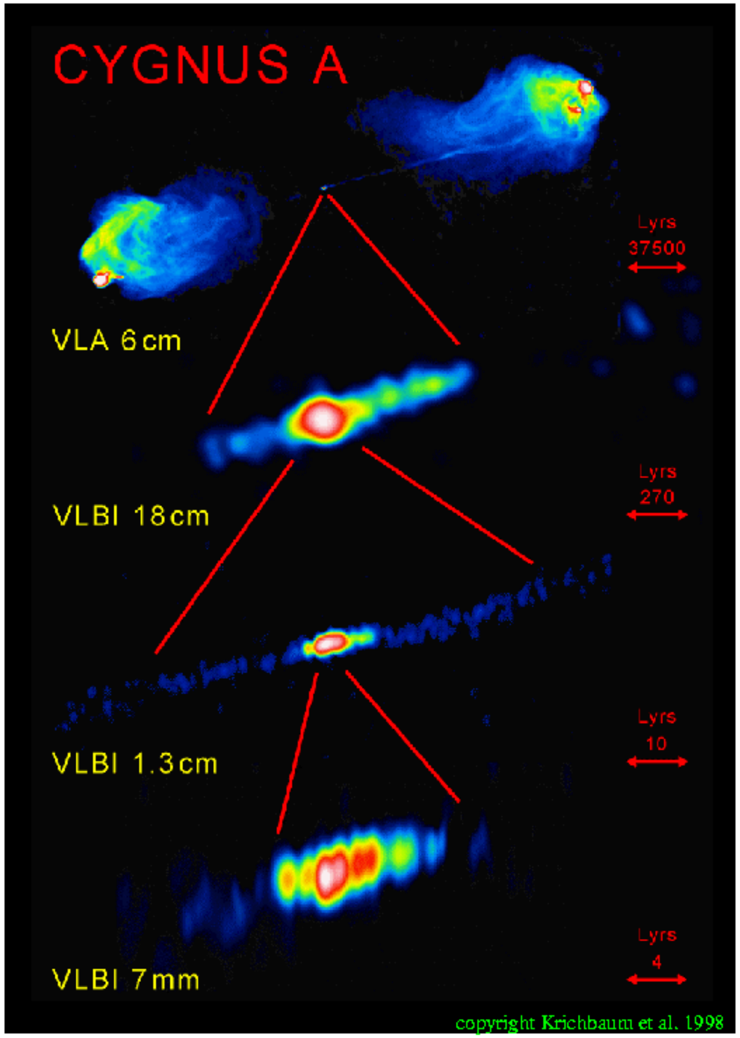


- They noticed that while double structure is almost always present, component hot spots could be close to galaxy, or nearly at outer edges of lobes
- The 1st (top) is also of lower radio power than the 2nd (bottom)
- These came to be known as FRI and FRII

VLA map of Cyg A: faint jet clearly observed

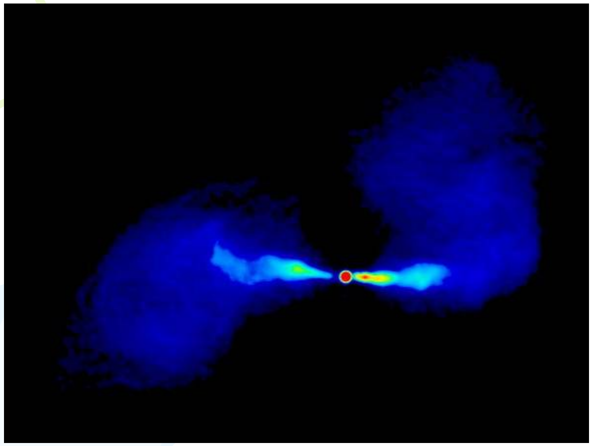


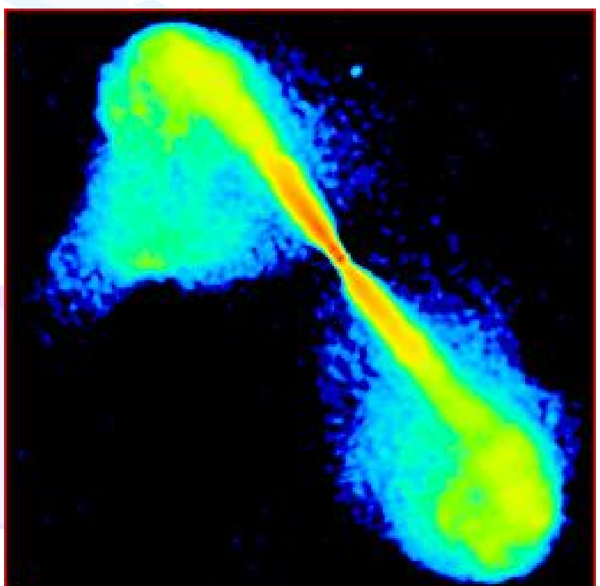
Another modern technique – VLBI – revealed inner jet



- The jet paradigm was clearly correct
- These thin channels efficiently carried the energy required to power the extended radio lobes
- Energy release in nucleus was gradual, not explosive
- Jets were ubiquitous

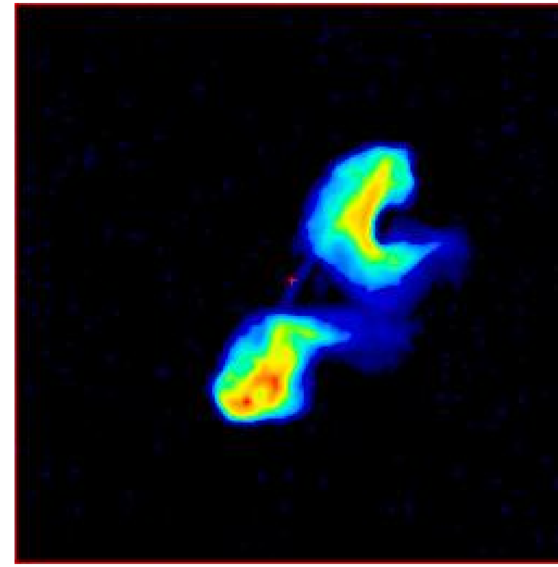
With good resolution, jets found in all double sources

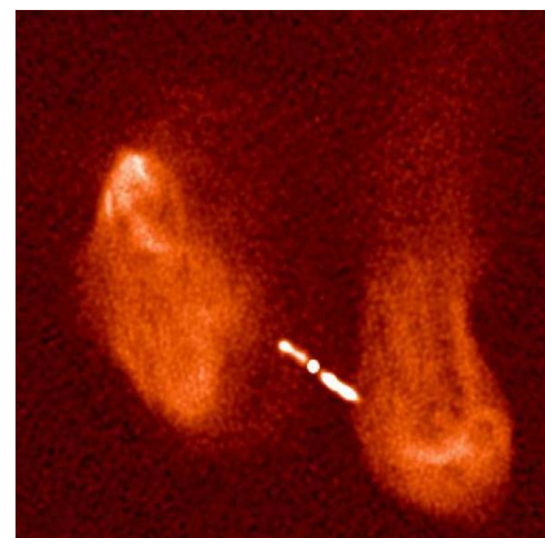




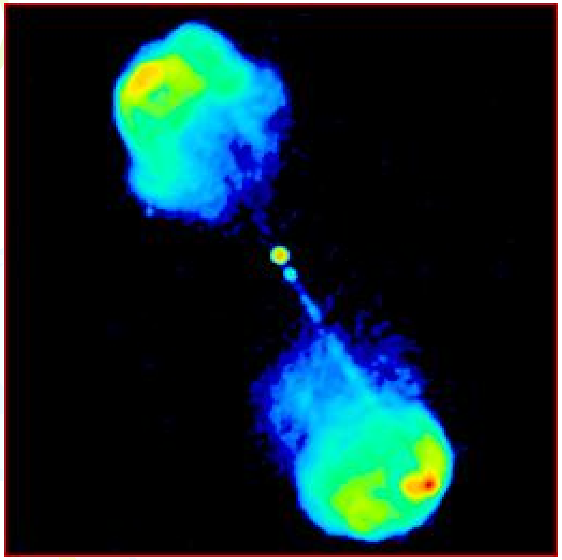
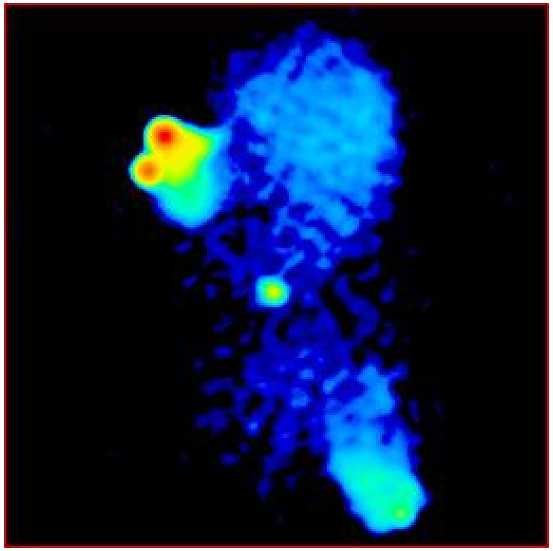
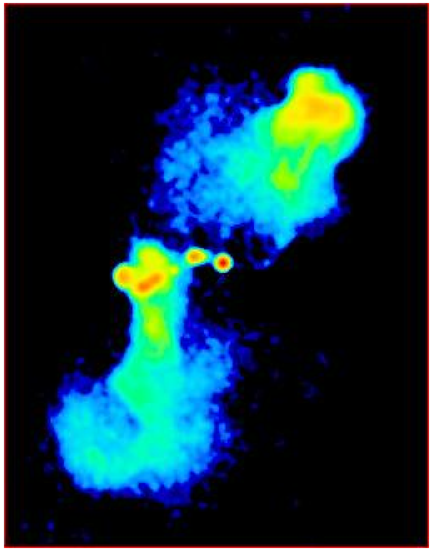
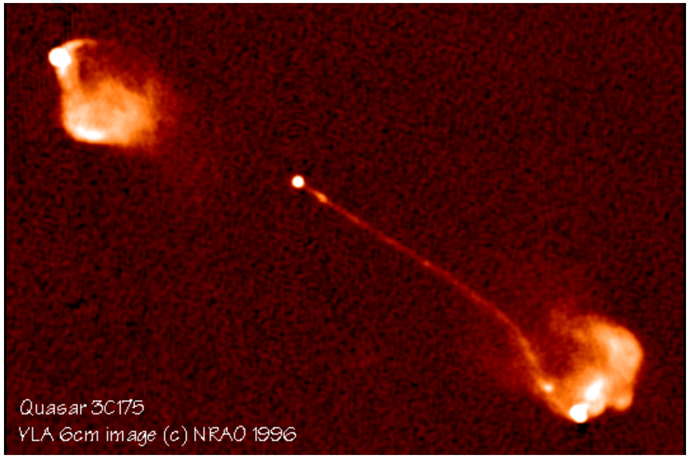
Both FR I (3C 272.1 & 296) and FR II (3C 28 & 3C 288) radio galaxies were found to have jets

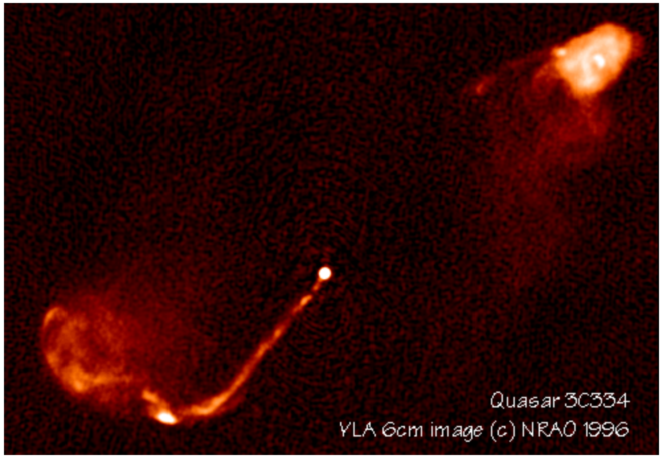
Jets are relatively brighter and equal in the FR I type galaxies



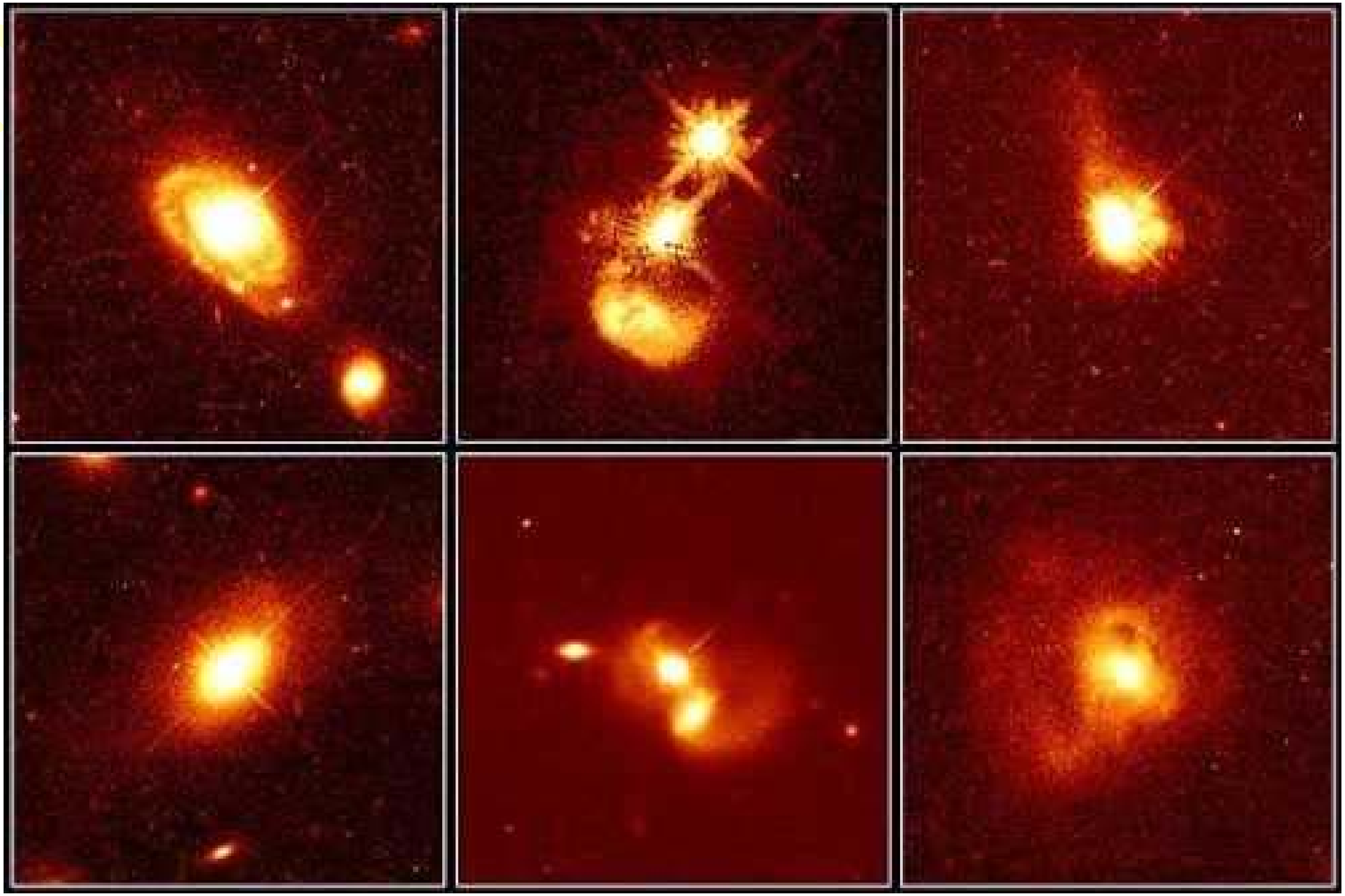


One-sided jet emission found in almost all quasars



HST observations now show quasars are galaxy nuclei



Next lecture: tomorrow

Introduction to cosmology: from Steady State controversy to CMB